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a Division of
The American Association of Petroleum Geologists

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JOURNAL OF SEDIMENTARY PETROLOGY, VOL. 3, NO. 1, PP. 3-29, FIGS. 1-4,
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THE SIZE-DISTRIBUTION OF HEAVY MINERALS WITHIN A WATER-LAID SANDSTONE

WILLIAM W. RUBEY[1]
U. S. Geological Survey, Washington, D.C.

ABSTRACT

The factors that control the distribution of heavy minerals in natural sandstones are so numerous and complex that their separate effects are difficult or even impossible to untangle. However, a theoretical approach to the problem indicates something of the relative importance of each.

Factors such as differences in the density and hardness of the various minerals, differences in the original size of the various mineral grains in the source rock, the amount of abrasion that all grains have undergone during transportation, the different settling velocities of the various grains at the site of deposition, and the degree of sorting to which all grains were subjected there—all these factors seem competent to cause large variations in the relative abundance of various minerals in different samples of deposits that have been derived from exactly the same source rock and also in different size fractions of each of the samples. Certain of the factors, such as abrasion, tend to concentrate the heavier minerals in those samples that are predominantly finer grained; whereas other factors, such as sorting, tend to concentrate the heavier minerals in the finer grained portions of each sample, regardless of whether that sample is predominantly fine-grained or coarse-grained.

The selective effects upon different minerals of the various influences, as deduced from theoretical considerations, appear to be confirmed by the evidence of actual sand samples. These effects seem sufficiently large to merit attention when using heavy mineral suites as a basis for correlation or for inferences about the character of source rock. Unless all the samples to be compared are of approximately the same grain size and the same degree of sorting, it is suggested that, in order to make allowances for these effects, heavy mineral separates be taken from *two* selected size fractions of each sample—one, representing the same *actual* grain size, the other, the same *relative* grain size in each sample.

INTRODUCTION

Sedimentary petrologists are familiar with the fact that heavy minerals tend to be concentrated within the finer grained portions of sandstones and that this concentration is due largely to processes of sedimentation.[2] Yet it may be of interest to review the various factors that influence the size-distribution of different mineral grains and to point out the differences, both apparent and real, in the heavy mineral suites of different samples that may result, even among sands that have been derived from the same source rocks.

These effects were called very forcibly to the writer's attention by a comparison of the heavy minerals that occur in two Pleistocene terrace deposits along Mississippi and Illinois rivers in

[1] Published with the permission of the Director of the U. S. Geological Survey and the Chief of the State Geological Survey of Illinois.

[2] Mackie, William, The principles that regulate the distribution of particles of heavy minerals in sedimentary rocks, as illustrated by the sandstones of the north-east of Scotland: *Trans. Edinburgh Geol. Soc.*, vol. 11, pp. 138-164, 1923.

the Hardin and Brussels quadrangles, Ill.[3] Many of the samples collected from different rock formations in this area were subjected to various types of commercial tests by members of the State Highway Department of Illinois, the Department of Ceramics of the University of Illinois, and the Illinois Geological Survey. Samples from two stream deposits, one of Illinoian age and the other of Wisconsin age, were sieved and examined to determine the nature of rock particles and heavy minerals by H. B. Willman of the State Geological Survey. Inasmuch as reconnaissance studies outside the area of the Hardin and Brussels quadrangles had indicated that these two deposits may become important reference-beds in deciphering the river history of this general region, it seemed worth while to examine Willman's data for any suggestions of petrographic differences that might supplement the physiographic and stratigraphic criteria by which the two terrace deposits are distinguished. But, to the writer's surprise, these data were found to indicate that the heavy mineral assemblages depend, not upon whether a sample came from the Illinoian or the Wisconsin deposit, but upon the coarseness or fineness of the particular sample. For example, the coarsest grained and the finest grained samples that were examined both came from the Wisconsin deposit, yet these two samples were reported to contain the extreme differences in heavy mineral assemblages.

[3] Rubey, W. W., Geology of the Hardin and Brussels quadrangles, Ill.: *Illinois Geol. Survey, Bull.* (Awaiting publication.)

It seemed desirable to re-examine the samples and for this purpose the original heavy mineral separates were very kindly loaned to the writer by J. E. Lamar of the State Geological Survey. Re-examination completely confirmed Mr. Willman's reports in all essential matters. Epidote, kyanite, andalusite, rutile, and hypersthene were found to be increasingly abundant in the successively coarser grained samples, and magnetite, ilmenite, zircon, muscovite, and biotite increasingly abundant in the successively finer grained samples. Six other mineral species were found in the samples and, of these, the relative abundance of four seem also to be dependent upon the grain size of the sample. However, the evidence regarding the four additional minerals is not conclusive and, for the present purpose, it will suffice to point out the relationship suggested by the ten minerals whose occurrence clearly varies with the grain size of the samples. Of these ten minerals, the five that are clearly most abundant in the finer grained samples are either heavier or softer than the five minerals that occur most abundantly in the coarser grained samples. Furthermore, detailed comparisons of the samples seem to show that this same relationship also governs the distribution of fragments of lighter materials, such as quartz, chert, and dark and light igneous rocks. In other words, these samples indicate that, other things being equal, the grains of heavier and softer minerals tend to be concentrated in finer grained samples and the grains of lighter and harder minerals in coarser grained samples.

This empirical observation is, of course, far from conclusive; and the series of efforts made to test the validity of the generalization led to the preparation of the present paper. The writer wishes to acknowledge gratefully the helpful criticism received from many of his colleagues of the U. S. Geological Survey, particularly W. H. Bradley and M. I. Goldman, who suggested many needed revisions of the first draft of the manuscript.

EXPECTED DISTRIBUTION OF HEAVY MINERALS ACCORDING TO STOKES' LAW

The probable cause of the concentration of heavy minerals within the finer grained portions of sandstones can perhaps best be approached by discussing the distribution of heavy minerals that might be expected in the simplest imaginable case—some theoretical deposit of sand about which all the conditions of source, transportation, and deposition are known. Let us assume that the source rock from which this sandstone was derived is made up entirely of quartz, magnetite, and tourmaline and has such a homogeneous composition that the proportionate abundance of these three minerals remains essentially the same whatever the grain size.

If the particles produced by the breaking up of this source rock were very soon entrained by flowing water, carried a short distance, and then deposited, many of the selective effects on different minerals of weathering and abrasion and of different agents of transportation would be slight. If, in addition, the relative velocities with which quartz, magnetite, and tourmaline grains are carried and deposited in water are known, it becomes possible to estimate the size-distribution of the heavy mineral grains that would be carried along and deposited with the different sized quartz grains.

To be more specific, let us take any random sample from this sandstone deposit and determine by some method the complete size-distribution of the quartz grains that were deposited in it (See Fig. 1). Then, the relative abundance of each different size of the quartz grains in the deposit and the relative abundance of quartz and magnetite at the source being known, we need only the relative settling velocities of quartz and magnetite grains in order to determine the complete size-distribution of the magnetite grains in the deposit. This use of settling velocities to determine the sizes of grains of different minerals that would be deposited together involves no particular assumptions about the mode of transportation of the grains nor does it imply that all the grains in a given deposit have the same settling velocity. Obviously, small grains that fell from near the bottom of a muddy fluid might reach the bottom long before larger grains that started falling from near the surface of the fluid. The only assumption involved here is that, whatever the conditions may have been which permitted the deposition of quartz grains of a certain size, these conditions would also permit the deposition of magnetite grains that had the same settling velocity.

The velocities with which different particles fall through a fluid depend chiefly upon the density and volume of the particles and the density and

viscosity of the fluid. It is true that other factors,[4] especially differences of shape, also influence settling velocities —as an extreme example, flat micaceous particles have a much larger surface area opposed to the currents of water than spherical particles of the same volume and density and, for that reason, the flat particles are picked up by gentle currents, fall slowly, and are deposited along with much smaller, more spherical particles. Nevertheless, the effect of the more important of the various factors can conveniently be summed up in Stokes' law. This law states that the settling velocities of essentially spherical particles vary as the square of the particle diameters, as the effective density of the particle in the fluid, and inversely as the viscosity of the fluid. Experimental studies[5] have shown that this law holds closely for particles with diameters between 0.0002 and about 0.2 millimeters (that is, for grains of clay, silt, and very fine sand). Larger particles depart more and more from Stokes' law until quartz grains with diameters greater than about 1.5 millimeters (that is, particles of very coarse sand and gravel) fall with velocities proportional to the square root instead of the square of the diameters.

If Stokes' law can be used for estimating settling velocities, then the relative sizes of a quartz grain and a magnetite grain that have the same settling velocity in water can be found.

According to Stokes' law,

where,

$$v = \frac{g}{18} \cdot \frac{\rho_q - \rho_w}{\eta} d_q^2 = \frac{g}{18} \cdot \frac{\rho_m - \rho_w}{\eta} d_m^2$$

where

v = settling velocity of both grains, measured in centimeters per second

ρ_q = specific gravity of quartz grain = 2.66

ρ_m = specific gravity of magnetite grain = 5.18

ρ_w = specific gravity of water = 1.00

d_q = diameter of quartz grain, measured in centimeters

d_m = diameter of magnetite grain, measured in centimeters

η = coefficient of viscosity of the water (a constant under these conditions)

g = acceleration due to gravity

Then,

$$(2.66 - 1.00)\, d_q^2 = (5.18 - 1.00)\, d_m^2$$

and $$d_m = \sqrt{\frac{2.66 - 1.00}{5.18 - 1.00}}\, d_q = 0.63 d_q$$

That is, a magnetite grain only 0.63 mm. in diameter would fall through water with the same velocity as a quartz grain 1.00 mm. in diameter.

The effects of probable departures from Stokes' law are discussed more fully in another part of this paper. However, if we may here provisionally accept it as a basis for estimating the relative sizes of all magnetite and quartz grains that have the same settling velocity, it then becomes possible to determine the size-distribution of

[4] See also Rubey, W. W., Lithologic studies of fine-grained Upper Cretaceous sedimentary rocks of the Black Hills region: *U. S. Geol. Survey Prof. Paper* 165, pp. 17-18, 23-24, 26-27, 1930.

[5] For references see *Idem.*, p. 18; Rubey, W. W., Settling velocities of gravel, sand, and silt particles: *Amer. Jour. Sci.*, vol. 25, 5th ser., pp. 325-338, 1933; and p. 17 of the present paper.

the magnetite grains that, under these assumed conditions, would be deposited along with the quartz grains in a random sample of the sandstone. If it is known that the source rocks were furnishing some quartz grains of essentially all sizes and we find that the sample contains no quartz grains with diameters less than 0.15 mm. (Fig. 1), this would mean that any still finer grains supplied at the source must have been kept in suspension and swept past the site of deposition by the currents that laid down the sandstone. Similarly, if the sample contains no quartz grains with diameters more than 6.6 mm., this means that the currents were not swift enough to transport any of the still larger grains to the site of deposition. And furthermore, the fact that quartz grains with diameters of 1.0 mm. occur most abundantly in the sample would indicate that the complex of currents at and above the site of deposition were, on the average, best able to transport to and deposit there quartz grains of this particular size.

Inasmuch as the assumed source rock had a homogeneous composition, it follows from Stokes' law that the smallest magnetite grains laid down with these quartz grains would be 0.094 (that is, 0.63×0.150) mm. in diameter, the largest magnetite grains 4.16 (that is, 0.63×6.6) mm. in diameter and the most abundant magnetite grains 0.63 mm. in diameter. In other words, the magnetite grains would be concentrated in the finer grained portions of the sample. If the magnetite grains were known to be, say, 1/10 as abundant in the source rock as the quartz grains, the complete size-distribution or frequency curve of the magnetite grains could be worked out and represented as in Figure 1.

The same method of attack would give the complete size-distribution of the tourmaline grains. If the specific gravity of the tourmaline is 3.09, then under Stokes' law a tourmaline grain

$$0.89 \left(= \sqrt{\frac{2.66 - 1.00}{3.09 - 1.00}}\right) \text{ mm. in di-}$$

ameter would fall through water with the same velocity as a quartz grain 1.00 mm. in diameter. Hence, in this sample, there would be no tourmaline grains less than 0.133 mm. in diameter and none more than 5.87 mm. in diameter, and those with diameters of 0.89 mm. would occur most abundantly. In other words, the tourmaline grains would be concentrated in portions of the sample intermediate in grain size between those of the quartz and magnetite concentrations. If the tourmaline grains occur in the source rock in, let us say, the same proportions as the magnetite grains, their frequency curve could be worked out in the same manner (Fig. 1).

In order to contrast clearly the frequency curves of the different minerals in Fig. 1, an unreasonably high proportion of magnetite and tourmaline to quartz has been assumed. To make the sample appear more nearly comparable with an actual one, a more reasonable $\frac{\text{quartz}}{\text{magnetite}}$ and $\frac{\text{quartz}}{\text{tourmaline}}$ ratio of 100 to 1 might have been taken. Furthermore, it is obvious that, had we chosen a somewhat finer grained sample but one with exactly the same type of sort-

ing, the distribution or frequency curves of the quartz, magnetite, and tourmaline in it would have had precisely the same shapes and relative positions as those in the coarser sample but their actual positions would all be shifted the same distance toward the smaller grain sizes.

For purposes of later comparison, let us take such a finer grained sandstone with exactly the same type of sorting as the first sample but with $\frac{\text{quartz}}{\text{magnetite}}$ and $\frac{\text{quartz}}{\text{tourmaline}}$ ratios of 100 to 1 and with all grains only $\frac{1}{2.828}$ $\left(=\frac{1}{(1.414)^3}\right)$ as large (that is, with the smallest quartz grains 0.053 instead of 0.150 mm. in diameter, the largest quartz

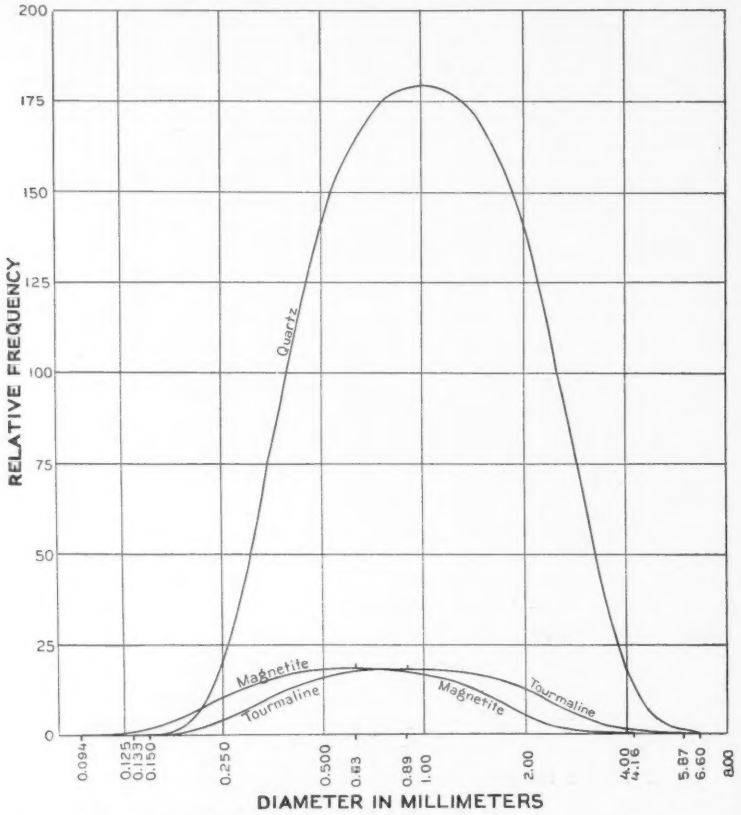

FIG. 1. Complete size-distribution or frequency curve of quartz, tourmaline, and magnetite grains within a well-sorted sandstone, according to Stokes' law.

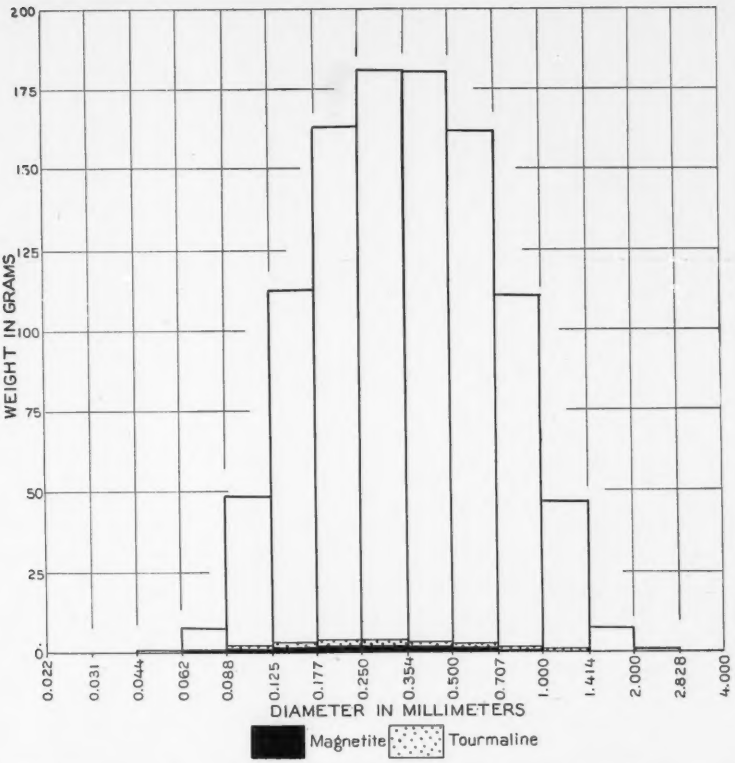

FIG. 2. Pyramidal diagram or histogram of entire sample showing distribution, between certain sieve limits, of quartz, tourmaline, and magnetite grains within a well-sorted medium grained sandstone, according to Stokes' law.

grains 2.33 instead of 6.6 mm. in diameter, and the most abundant quartz grains 0.354 instead of 1.000 mm. in diameter). Let us separate the grains in this second sample by means of a series of sieves with mesh sizes that increase by the ordinary sieve ratio of $\sqrt{2}$ or 1.414 and then weigh separately the portions retained on each sieve. When this is done, the data for the frequency curves of the three minerals can be replotted as one pyramidal diagram or histogram[6] which shows the distribution of 1,000 grams of quartz, 10 grams of tourmaline, and 10 grams of magnetite between the several diameters used as mesh sizes in the different sieves. (See Fig. 2.)

The histogram of this second sample

[6] Wentworth, C. K., Methods of mechanical analysis of sediments: *Iowa Univ. Studies*, vol. 11, pp. 46-50, 1926.

is that of a moderately well-sorted medium grained sandstone in which the particles with diameters between 0.354 and 0.250 mm. constitute the *chief ingredient* or *maximum*[7] (or, stated in other terms, the median diameter of the sample is slightly less than 0.354 mm.). A third sample, still finer grained [with its particles only $\frac{1}{(1.414)^7}$ as large as those in the first sample (Fig. 1), and therefore only $\frac{1}{(1.414)^4}$ as large as those in the second sample (Fig. 2)] but with exactly the same degree of sorting, would obviously give a histogram of the same shape as Fig. 2 but displaced four sieve-units toward the smaller grain sizes. And a fourth sample, coarser grained [with its particles $(1.414)^2$ times as large as those in the first sample (Fig. 1), and therefore $(1.414)^5$ times as large as those in the second sample (Fig. 2)] but with exactly the same degree of sorting, would give the same shaped histogram displaced five sieve-units toward the coarser grain sizes.

TABLE 1. DISTRIBUTION BY WEIGHT, ACCORDING TO STOKES' LAW, OF MAGNETITE AND TOURMALINE GRAINS IN A SAMPLE OF WELL-SORTED MEDIUM GRAINED SANDSTONE. (Sorting same as that shown in Figs. 1 and 2.)

Limiting diameters of sieve unit in millimeters	Magnetite Weight in grams	Tourmaline* Weight in grams	Total "heavies" Weight in grams
0.031–0.044	0.005–	None	0.005–
0.044–0.062	0.16	0.005–	0.160+ to 0.165–
0.062–0.088	0.67	0.16	0.83
0.088–0.125	1.30	0.67	1.97
0.125–0.177	1.68	1.30	2.98
0.177–0.250	1.78	1.68	3.46
0.250–0.354	1.74	1.78	3.52
0.354–0.500	1.46	1.74	3.20
0.500–0.707	0.89	1.46	2.35
0.707–1.000	0.29	0.89	1.18
1.000–1.414	0.03	0.29	0.32
1.414–2.000	0.005–	0.03	0.030+ to 0.035–
2.000–2.828	None	0.005–	0.005–

* The value of 3.09, used for the specific gravity of the tourmaline, falls about midway in the reported range of tourmaline specific gravities and was chosen because it greatly reduces the labor of computation necessary to prepare this table. With its use, the quantity of tourmaline in one sieve unit is exactly the same as the quantity of magnetite in the next smaller sieve unit

Let us now remove by means of a suitable heavy liquid all the quartz grains from each of the 13 size fractions in the second or medium-grained sample (Fig. 2) and then determine the relative abundance of magnetite and tourmaline in each of the separate size fractions. For this particular sample, the frequency curve, the mineral densities, and Stokes' law give the quantities as shown in Table 1.

These quantities, plotted on an enlarged scale, are shown in the histogram of heavy minerals (Fig. 3B). A similar separation of quartz from the third sample (fine-grained) and the fourth sample (coarse-grained) would

[7] Udden, J. A., Mechanical composition of clastic sediments: *Geol. Soc. Amer., Bull.*, vol. 25, p. 658, 1914.

give the histograms shown in Fig. 3A and 3C.

If now we compare the heavy minerals found in some one sieve unit in each of these last three samples, we find that their relative abundance varies greatly.

The greater concentration of magnetite in the finer grained fractions of each sample means that, upon compar-

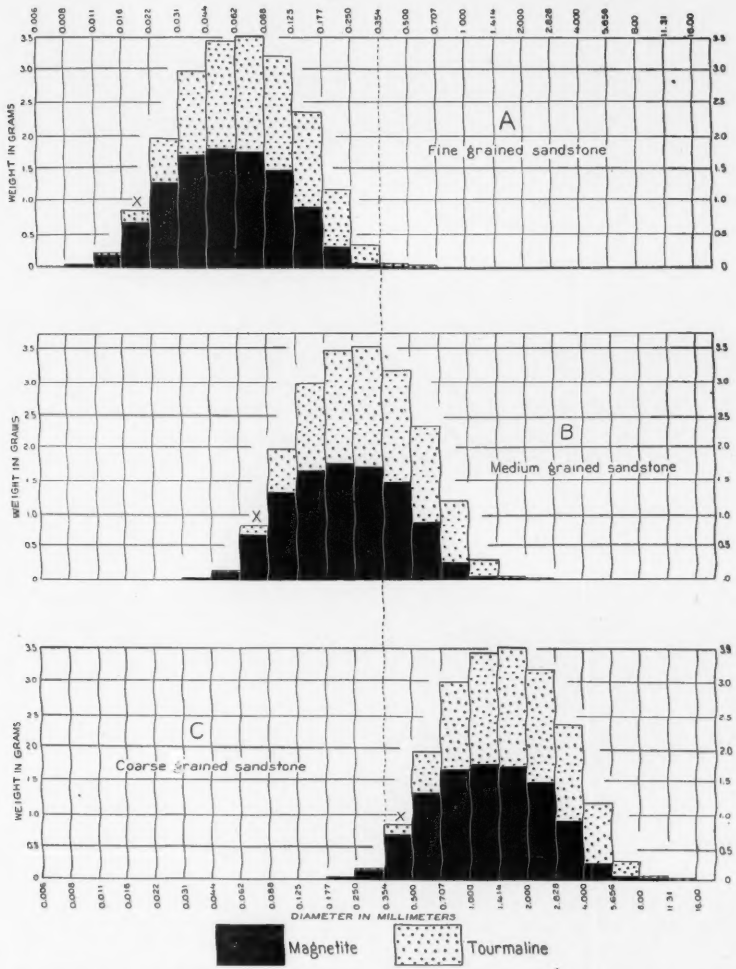

FIG. 3 A, B, and C. Pyramidal diagram or histogram of heavy minerals, showing distribution, between certain sieve limits, of tourmaline and magnetite grains within three samples of well-sorted sandstone, according to Stokes' law.

TABLE 2. RELATIVE ABUNDANCE, ACCORDING TO STOKES' LAW, OF DIFFERENT HEAVY MINERALS WITH DIAMETERS *Between 0.250 and 0.354 mm.*, IN THREE WELL SORTED SAMPLES (Sorting same as that shown in Figs. 1 and 2.)

Sample	Magnetite	Tourmaline	Total "heavies"
Fine-grained sandstone..... (Sample with minimum diameter of 0.013 mm., maximum diameter of 0.584 mm., and median diameter of 0.088 mm.—for quartz particles)	0.03 grams 9%	0.29 grams 91%	0.32 grams 100%
Medium-grained sandstone..... (Sample with minimum diameter of 0.053 mm., maximum diameter of 2.33 mm., and median diameter of 0.354 mm.—for quartz particles)	1.74 grams 49%	1.78 grams 51%	3.52 grams 100%
Coarse-grained sandstone..... (Sample with minimum diameter of 0.300 mm., maximum diameter of 13.2 mm., and median diameter of 2.00 mm.—for quartz particles)	0.16 grams 97+%	0.005− grams 3−%	0.160+ to 0.165− grams 100%

ing the relative abundance of the different heavy minerals of some particular grain size in different samples (that is, upon comparing the heavy minerals in the finer fractions of the coarse samples with those in coarser fractions of fine samples), magnetite seems to occur in greater abundance in the coarser samples, even though it is in fact equally abundant in all three samples.

The comparisons just made were of the relative abundance of magnetite and tourmaline in the same sieve unit of each sample. If, instead, we had followed another laboratory procedure and made the comparisons of different samples by considering all the heavy mineral grains smaller than some one sieve size, we would not have found so great a variation in relative abundance.

TABLE 3. RELATIVE ABUNDANCE, ACCORDING TO STOKES' LAW, OF DIFFERENT HEAVY MINERALS WITH DIAMETERS *Less than 0.354 mm.*, IN THREE WELL SORTED SAMPLES. (Sorting same as that shown in Figs. 1 and 2.)

Sample	Magnetite	Tourmaline	Total "heavies"
Fine-grained sandstone..... (Sample with minimum diameter of 0.013 mm., maximum diameter of 0.584 mm., and median diameter of 0.088 mm.—for quartz particles)	10.00 grams 50%	9.97 grams 50%	19.97 grams 100%
Medium-grained sandstone..... (Sample with minimum diameter of 0.053 mm., maximum diameter of 2.33 mm., and median diameter of 0.354 mm.—for quartz particles)	7.33 grams 57%	5.59 grams 43%	12.92 grams 100%
Coarse-grained sandstone..... (Sample with minimum diameter of 0.300 mm., maximum diameter of 13.2 mm., and median diameter of 2.00 mm.—for quartz particles)	0.16 grams 97+%	0.005− grams 3−%	0.160+ to 0.165− grams 100%

With this laboratory procedure, magnetite would assuredly be found in all the samples but tourmaline might escape notice in the coarse-grained sandstone. It is important to note that both types of comparison would make the magnetite appear more abundant than the tourmaline in the coarser grained samples.

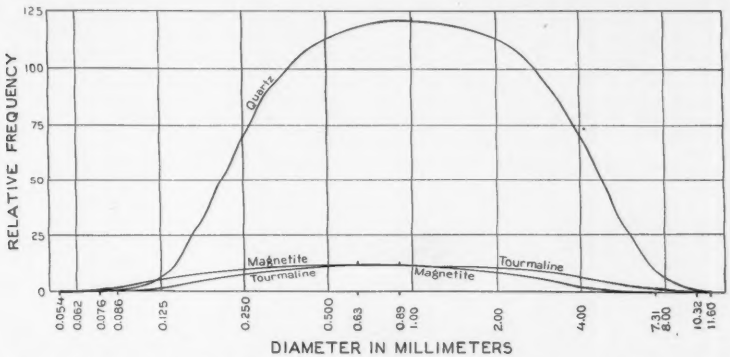

FIG. 4. Complete size-distribution or frequency curve of quartz, tourmaline, and magnetite grains within a poorly sorted sandstone, according to Stokes' law.

It is true that slight differences, such as some of those given above, in the relative abundance of heavy minerals in different samples are perhaps seldom used as a basis for the correlation of sandstones. But large differences in the relative abundance (and especially the mere presence or absence) of certain minerals in a rock are often used for correlation when more trustworthy criteria, like the occurrence of peculiar varieties, can not be found. Also, the general assemblages of heavy minerals in sedimentary rocks (that is, the presence and absence of certain species and the relative abundance of each) are sometimes used as indicators of the type or types of source rocks that were exposed to erosion at the time of sedimentation. Yet those who have estimated the relative abundance of different minerals in a number of samples probably will admit that minerals, like the magnetite and tourmaline in Table 2, which range from more than 90 per cent in some samples to less than 10 per cent in others, might sometimes be reported, respectively, as "flood" or as "absent," especially when the effects of minor variations in technique of separation and the accidents of sampling for microscopic study are considered.[8] That is, two sandstones derived from the same source rocks and deposited at the same time might, un-

[8] Wentworth, C. K., The accuracy of mechanical analysis: *Amer. Jour. Sci.*, 5th ser., vol. 13, pp. 404-406, 1927.
Smithson, Frank, The reliability of frequency-estimations of heavy mineral suites: *Geol. Mag.*, vol. 67, pp. 134-136, 1930.
Ewing, C. J. C., A comparison of the methods of heavy mineral separation: *Geol. Mag.*, vol. 68, pp. 136-140, 1931.
Dryden, A. L., Jr., Accuracy in percentage representation of heavy mineral frequencies: *Proc. Nat. Acad. Sci.*, vol. 17, pp. 233-238, 1931.

der such circumstances, be interpreted as wholly unrelated to one another.

THE EFFECT OF DIFFERENT TYPES OF SORTING

Thus far, in order to eliminate some of the countless factors that make the interpretation of actual sandstones complicated and difficult, it has been assumed that all the samples compared have had exactly the same degree of sorting. Now, to determine the effect of the degree of sorting, let us take samples which, instead of being moderately well-sorted, are rather poorly sorted, with frequency curves of the shape shown in Fig. 4. From Stokes' law, the frequency curves of the magnetite and tourmaline associated with the quartz can be worked out; and, from these frequency curves, histograms can be constructed which show the distribution of 1,000 grams of quartz, 10 grams of tourmaline, and 10 grams of magnetite in poorly sorted fine-grained, medium-grained, and coarse-grained sandstones. Separating off the quartz as before, we can then make comparisons analogous to those made with the well sorted samples.

It is evident from these tables that the variation in apparent abundance of different heavy minerals in a series of poorly sorted samples is considerably less than it is in a series of well sorted samples of the same average grain size. This, of course, is the expected result, for, had there been no sorting whatever, the percentages of the different minerals would have remained exactly

TABLE 4. RELATIVE ABUNDANCE, ACCORDING TO STOKES' LAW, OF DIFFERENT HEAVY MINERALS WITH DIAMETERS *Between 0.250 and 0.354 mm.*, IN FIVE POORLY SORTED SAMPLES. (Sorting same as that shown in Fig. 4.)

Sample	Magnetite	Tourmaline	Total "heavies"
Very fine-grained sandstone..... (Sample with minimum diameter of 0.005 mm., maximum diameter of 0.73 mm., and median diameter of 0.062 mm.—for quartz particles)	0.08 grams 17%	0.39 grams 83%	0.47 grams 100%
Fine-grained sandstone..... (Sample with minimum diameter of 0.008 mm., maximum diameter of 1.03 mm., and median diameter of 0.088 mm.—for quartz particles)	0.39 grams 35%	0.73 grams 65%	1.12 grams 100%
Medium-grained sandstone..... (Sample with minimum diameter of 0.030 mm., maximum diameter of 4.10 mm., and median diameter of 0.354 mm.—for quartz particles)	1.20 grams 49%	1.24 grams 51%	2.44 grams 100%
Coarse-grained sandstone..... (Sample with minimum diameter of 0.172 mm., maximum diameter of 23.2 mm. and median diameter of 2.00 mm.—for quartz particles)	0.64 grams 71%	0.26 grams 29%	0.90 grams 100%
Very coarse-grained sandstone..... (Sample with minimum diameter of 0.243 mm., maximum diameter of 32.8 mm., and median diameter of 2.828 mm.—for quartz particles)	0.26 grams 87%	0.04 grams 13%	0.30 grams 100%

TABLE 5. RELATIVE ABUNDANCE, ACCORDING TO STOKES' LAW, OF DIFFERENT HEAVY MINERALS WITH DIAMETERS *Less than 0.354 mm.*, IN FIVE POORLY SORTED SAMPLES. (Sorting same as that shown in Fig. 4.)

Sample	Magnetite	Tourmaline	Total "heavies"
Very fine-grained sandstone..... (Sample with minimum diameter of 0.005 mm., maximum diameter of 0.73 mm., and median diameter of 0.062 mm.—for quartz particles)	10.00 grams 50%	9.91 grams 50%	19.91 grams 100%
Fine-grained sandstone..... (Sample with minimum diameter of 0.008 mm., maximum diameter of 1.03 mm., and median diameter of 0.088 mm.—for quartz particles)	9.91 grams 51%	9.52 grams 49%	19.43 grams 100%
Medium-grained sandstone..... (Sample with minimum diameter of 0.030 mm., maximum diameter of 4.10 mm., and median diameter of 0.354 mm.—for quartz particles)	6.61 grams 55%	5.41 grams 45%	12.02 grams 100%
Coarse-grained sandstone..... (Sample with minimum diameter of 0.172 mm., maximum diameter of 23.2 mm., and median diameter of 2.00 mm.—for quartz particles)	0.94 grams 76%	0.30 grams 24%	1.24 grams 100%
Very coarse-grained sandstone..... (Sample with minimum diameter of 0.243 mm., maximum diameter of 32.8 mm., and median diameter of 2.828 mm.—for quartz particles)	0.30 grams 88%	0.04 grams 12%	0.34 grams 100%

the same in every size fraction of each sample. Yet it is interesting to note that, even in these poorly sorted samples, the percentage differences are still very large and, if samples somewhat finer and somewhat coarser grained (the "very fine-grained sandstone" and the "very coarse-grained sandstone" of Tables 4 and 5) than those shown in Tables 2 and 3 are compared, the differences are virtually the same as those in the series of well sorted samples.

It is also worthy of note that the apparent contrasts in mineral proportions are large enough to be significant when samples with the same average grain size but with different degrees of sorting are compared (Table 6). This, likewise, is the expected result for, had this same size fraction (or, for that matter, any other size fraction) been

TABLE 6. RELATIVE ABUNDANCE, ACCORDING TO STOKES' LAW, OF DIFFERENT HEAVY MINERALS WITH DIAMETERS *Between 0.250 and 0.354 mm.*, IN SAMPLES OF FINE-GRAINED SANDSTONE (median diameter about 0.088 mm. in both samples but maximum and minimum diameters not the same in both samples).

Sample	Magnetite	Tourmaline	Total "heavies"
Well-sorted.....	0.03 grams 9%	0.29 grams 91%	0.32 grams 100%
Poorly-sorted.....	0.39 grams 35%	0.73 grams 65%	1.12 grams 100%

taken from an absolutely unsorted sample, it would have contained exactly equal amounts of magnetite and tourmaline.

These comparisons have shown, that, among grains of the same diameter from samples of the same average coarseness, the differences in relative abundance of various minerals increase with the degree of sorting. Hence, it is pertinent to inquire whether or not the degree of sorting taken to represent the "well-sorted" samples is so extreme that it is but rarely found in nature. The data for the histogram of any one of the "well-sorted" samples (Fig. 2 for example) can readily be recast into a form suitable for comparison with the collections of mechanical analyses published by Udden[9] and Wentworth.[10] Inspection of these analyses will show that, judged either by the relative height of the maximum grade above the rest of the sample or by the number of grade sizes, the "well-sorted" samples discussed in this paper are somewhat less sorted than many fluvial sands and much less sorted than most eolian and beach sands. Had more perfectly sorted samples been chosen for the above comparisons, the apparent differences in heavy mineral assemblages with varying grain size of the samples would have been much greater.

We have also assumed that the size-frequency curves of both the well-sorted and the poorly-sorted samples are smooth, simple curves which are symmetrical on either side of one chief constituent or maximum grade.[11] Frequency curves with marked irregularities and secondary maxima[12] would, of course, give rise to comparable irregularities in the relative abundance of different mineral species in certain size fractions; yet it is clear that irregularities of this sort in the frequency curves can, in the aggregate, neither increase nor decrease the contrasts in mineral proportions caused by differences in grain size or degree of sorting.

The effect of symmetry or asymmetry of the frequency curves perhaps requires an additional word. Sandstones with the perfectly symmetrical size-distribution assumed for our theoretical samples are no doubt rare in nature. Nevertheless, the distribution curves of many actual samples are approximately symmetrical, and departures from the assumed symmetry would not invalidate the conclusions reached in this paper. Of the two possible types of asymmetry, those in which more than half of the grains are larger than the chief ingredient appear to be somewhat the commoner. Asymmetrical distribution of this more common type would tend to increase the $\frac{\text{magnetite}}{\text{tourmaline}}$ ratio in the finer grained portions and decrease it in the coarser grained portions of a sample. Asymmetrical distribution of the opposite type (more than half of the grains would tend to decrease the $\frac{\text{magnetite}}{\text{tourmaline}}$

[9] *Op. cit.*, pp. 693-727.
[10] Wentworth, C. K., The mechanical composition of sediments in graphic form: *Univ. Iowa Studies*, vol. 14, pp. 36-126, 1932.
[11] Udden, *Op. cit.*, p. 658.
[12] Udden, *Op. cit.*, pp. 736-737.

smaller than the chief constituent) ratio in the finer grained portions and increase it in the coarser grained portions of a sample. But, though the exact values of the ratios would be different for the various types of asymmetrical distribution, all types would give a concentration of the heavier minerals in the finer portions of a sample just as does a symmetrical distribution. Consequently, a comparison of the grains from different samples retained between some one pair of sieves would show a greater relative abundance of magnetite in the coarser grained samples, very much as does the symmetrical distribution represented in Figs. 3 A, B, and C. The effect of any asymmetry is, therefore, such that no important qualification is required of the conclusions that have so far been reached about the apparent variation of heavy mineral assemblages with varying grain size or degree of sorting of the samples.

THE EFFECT OF DEPARTURES FROM STOKES' LAW

For the purpose of estimating the relative settling velocities of the quartz, magnetite, and tourmaline grains, we have assumed that Stokes' law holds for all grain sizes. However, this law applies only so far as viscosity is the controlling factor in the resistance of the settling fluid. Theoretical considerations and experimental evidence indicate that for larger particles the resistance is dominated by the impact rather than the viscosity of the fluid and that very coarse sand and gravel fall with velocities which vary as the square root instead of the square of the diameters.[13]

If all particles in a sample were so large that their settling velocities followed this square root law, then the relative sizes of a quartz grain and a magnetite grain that have the same velocity in water could be found, for, using the same notation as that on p. 6.

$$v = \sqrt{2/3.g. \frac{\rho_q - \rho_w}{\rho_w} d_q}$$

$$= \sqrt{2/3.g. \frac{\rho_m - \rho_w}{\rho_w} d_m}$$

Then $(2.66 - 1.00)\, d_q = (5.18 - 1.00)\, d_m$ and $d_m = 0.397\, d_q$

That is, a large grain of quartz would fall through water at the same velocity as a magnetite grain with a diameter only $\frac{397}{1000}$ as large [instead of $\frac{63}{100}$, the expected ratio under Stokes' law]. And a tourmaline grain only $\frac{794}{1000}$ [instead of $\frac{89}{100}$]; the diameter of the quartz grain would fall with the same velocity. Hence, the frequency curves of the magnetite and tourmaline grains, though unchanged in shape, would be shifted much farther away from the frequency curve of the quartz grains than those shown in Figs. 1 and 4.

[13] Richards, R. H., Velocity of galena and quartz falling in water: *Trans. A.I.M.E.*, vol. 38, pp. 210-235, 1908.

Rubey, W. W., Settling velocities of gravel, sand, and silt particles: *Amer. Jour. Sci.*, vol. 25, 5th ser., pp. 325-338, 1933.

Furthermore, the magnetite curve would be shifted much farther than the tourmaline curve, thereby causing much greater differences in the $\frac{\text{magnetite}}{\text{tourmaline}}$ ratios of the coarse- and fine-grained portions of each sample.

If the Stokes' or square-of-the-diameter law holds for small grains (less than about 0.2 mm. in diameter) and the square-root-of-the-diameter law holds for large grains (more than about 1.5 mm. in diameter), then in a medium-grained sandstone, with many grains of intermediate sizes, the heavy minerals would be distributed very differently from those in a very coarse-grained sandstone or gravel or those in a very fine-grained sandstone or silt. In the sample of sandstone represented in Fig. 1, the smallest quartz grains (diameter of 0.150 mm.) would settle by the square-of-the-diameter law at approximately the same rate as magnetite grains with a diameter of 0.63×0.150 mm. or 0.094 mm., and the largest grains in this sample (diameter of 6.6 mm.) would settle by the square-root-of-the-diameter law at the same rate as magnetite grains with a diameter of 0.397×6.6 mm. or 2.62 mm. This would mean, not only that the magnetite would be finer grained than the quartz, but that the frequency curve of the magnetite would have a shape very different from that of the quartz curve because it would be condensed between narrower size limits. In other words, the magnetite grains would be much better sorted than the quartz grains with which they were deposited. This corollary seems to be confirmed by available data[14] on natural magnetite-bearing sands with particles that range between these two size limits. The degree of sorting of the tourmaline grains would, however, be affected much less than that of the magnetite grains because the two factors for tourmaline, 0.89 and 0.794, differ much less than those for magnetite. The net result of this more perfect sorting of the magnetite grains would be to increase still further the $\frac{\text{magnetite}}{\text{tourmaline}}$ ratio in the finer grained portions of a sample.

What we have just been saying is that the probable departures from Stokes' law would affect different samples differently, depending upon their prevailing grain sizes. In coarse sands and gravels, the frequency curve of the magnetite grains would be displaced much farther from the quartz curve than it would in very fine sands and silts, but the shape of the curve would remain the same. In medium-grained sands, however, the magnetite curve would be displaced only an intermediate distance but its shape would be changed greatly—the magnetite would be much better sorted than the quartz.

A general formula expressing the settling velocities of both large and small particles has been proposed elsewhere,[15] and it might perhaps be used to determine the relative diameters of quartz and magnetite grains, whether

[14] Udden, *Op. cit.*, pp. 733-734.

[15] Rubey, *Amer. Jour. Sci.*, vol. 25, pp. 325-338.

large, small, or medium sized, that have the same settling velocity.

$$v = \frac{\sqrt{2/3.g.\rho_w(\rho_q - \rho_w)d_q{}^3 + 36\eta^2} - 6\eta}{\rho_w d_q}$$

$$= \frac{\sqrt{2/3.g.\rho_w(\rho_q - \rho_w)d_m{}^3 + 36\eta^2} - 6\eta}{\rho_w d_m}$$

However, this general expression (here stated in the terminology used on p. 6) has not yet been tested adequately, and it seems to the writer that the computations necessary for such a determination would needlessly encumber the present paper. Suffice it here to state that graphic solutions based upon this general formula bear out the conclusion stated in the preceding paragraph. That is, the departures from Stokes' law tend to increase rather than decrease the irregularities in distribution of different mineral species within a sandstone; when these departures are taken into consideration, the heavier minerals still tend to be concentrated within the finer fractions of a sample; and, upon comparing some one grain size in samples of different coarseness (that is, upon comparing the relatively fine fractions of coarse samples with the relatively coarse fractions of fine samples), the coarser samples still appear to contain higher $\frac{\text{magnetite}}{\text{tourmaline}}$ ratios. In short, the estimation of relative settling velocities by means of Stokes' law does not exaggerate but, in fact, for the common size range of sand grains, it considerably minimizes the effect of water sorting upon the size-distribution of grains of different minerals.

THE EFFECT OF ABRASION DURING TRANSPORTATION

The sand grains in the samples we have been discussing were assumed to have traveled only a very short distance from their source to their site of deposition. But, had they been carried a considerable distance, the effects of mutual abrasion during transportation would have modified the results sufficiently to require attention.

It is doubtless true that most sand grains have, in their repeated cycles of transportation and deposition, been transported considerable distances and that they have therefore undergone appreciable abrasion. However, the principles that govern this abrasion and grinding down to smaller sizes are still too imperfectly known to permit quantitative estimates of the sort just attempted in dealing with settling velocities. To be sure, suggestions have been made that the abrasion of particles due to their transportation varies directly as the effective weight in water and the distance traveled[16] and inversely as the hardness of the particles.[17] These proposed relations may possibly apply quite strictly to rolling grains, for they have been found to hold closely for the largest pebbles in the gravel along the upper Rhine.[18] But moving water carries debris in various ways.[19] The larg-

[16] Sternberg, H., Cited by Barrell, Joseph, Marine and terrestrial conglomerates: *Geol. Soc. Amer. Bull.*, vol. 36, p. 327, 1925.

[17] Mackie, William, On the laws that govern the rounding of particles of sand: *Trans. Edinburgh Geol. Soc.*, vol. 7, pp. 298-311, 1897.

[18] Barrell, *op. cit.*, pp. 329-330.

[19] Gilbert, G. K., The transportation of debris by running water, *U. S. Geol. Survey Prof. Paper* 86, pp. 15, 26-34, 156, 223-224, 230, 1914.

est particles being carried at any one time are rolled along the bottom, the smallest ones are held in suspension, the particles of intermediate sizes travel by a process of leaping called saltation, and some particles of all sizes may move along the bottom by sliding or a kind of plastic flow. It seems very improbable that all the smaller particles being transported by suspension, saltation, and sliding should follow exactly the same law of abrasion as the rolling grains. Among these smaller particles, the distance of travel is not measured simply by the circumference and the number of revolutions of each grain, and some more complex relation probably holds.

For the present purpose, however, this qualification can perhaps be ignored and the generalization made that the abrasion of particles due to their transportation varies approximately as the volume, as the effective density (specific gravity — 1), as the distance of travel, and inversely as the true hardness of the different mineral grains. That is to say, the effect of transportation in any unit distance of travel would be to abrade most the largest grains of each mineral and to abrade least the smallest grains, thereby increasing the proportion of small grains. Different minerals, of course, would be affected differently by this process of comminution, for the heavier and softer minerals would suffer the greater loss in a unit distance of travel.

"True hardness" as here used means simply durability or resistance to wear. In general, this resistance of different minerals would be expected to increase as some function of their position or number in the ordinary Moh's scale of hardness, modified, however, in some minerals by such other factors as readiness of cleavage or rate of decomposition. The best readily available estimates of the resistance to abrasion of different minerals appear to be quantitative determinations of the resistance to scratching as measured with the sclerometer. Tests of this sort indicate[20] that a mineral with the hardness of tourmaline is about 2 or 2½ times as resistant to abrasion as a mineral with the hardness of magnetite. This lower resistance of the magnetite, together with its greater effective density in water (5.18 — 1.00 as against 3.09 — 1.00) would, therefore, lead us to expect that, in traveling a given distance, magnetite grains would be subjected to several times as much loss by abrasion as tourmaline grains of the same size.

At this point, it is well to call attention to another element of uncertainty which prevents us from making precise estimates of the amount of abrasion undergone by grains of different minerals. A unit distance of travel is not necessarily equivalent to a unit of time. The heavier grains (the larger ones and those of higher specific gravity) will, because of their greater mass and inertia, be transported less rapidly than the lighter grains.[21] Presumably the very smallest and lightest grains transported by a stream are accelerated during their long leaps until they attain a

[20] Jaggar, T. A., Jr., A microsclerometer, for determining the hardness of minerals: *Amer. Jour. Sci.*, vol. 4, 4th ser., p. 411, 1897.

[21] Gilbert, *op. cit.*, pp. 26, 29.

Daubrée, G. A., Géologie expérimentale, vol. 1, pp. 250-251, 1879; cited by Barrell, *op. cit.*, p. 327.

velocity essentially that of the water; whereas the very largest and heaviest grains (those that the stream is just able to transport) stop repeatedly and so have a very low average velocity; and the other particles of intermediate sizes and weights transported at the same time presumably travel at velocities intermediate between the velocity of the water and zero. That is, the heavier grains tend to lag behind the lighter ones. Therefore, since all grains do not travel with the same average velocity, the particular velocity of a given grain must be known in order to determine the amount of abrasion it undergoes in a unit of time.

The problem thus raised—the relative velocity of the water and the sand grains being transported—is of considerable importance, yet very little appears to be known about it. Manifestly, the actual velocity of the sediment in a stream should be known or else the load transported in a unit of time cannot be calculated accurately. But estimates of the total solids being eroded from drainage basins and of the total silt being carried into reservoirs have had to rest upon the rather improbable assumption that the sediment travels at exactly the same velocity as the water. Were it not for the fact that these estimates have also had to neglect the load dragged along the stream beds, the total sediment thus calculated would almost certainly be too great.

This uncertainty about the velocity of transportation of sand grains of different sizes and weights means that, although large heavy grains clearly suffer more loss by abrasion than small light grains in a unit distance of travel, it is not certain that the wear due solely to their own movement causes them to lose more in a unit of time. But there is an additional factor in abrasion, thus far neglected in this discussion, that tends to offset this uncertainty by increasing still further the wear per unit distance upon the heavier grains. This factor, which was clearly pointed out by Barrell,[22] is the abrasion of the slowly-moving heavy grains, not by their own movement, but by the continuous blast of rapidly-moving lighter grains always being swept past them. This process of wet-blasting appears to be of more than merely theoretical importance; if properly interpreted,[23] it accounts for the rapid disappearance of the quantities of pebbles and boulders being dumped into the Mississippi River by steep tributaries and caving banks of Pleistocene gravel.

The effect of this wet-blasting of the heavier, lagging grains thus augments the effect of the ordinary abrasion due to the particles' own movement. With continued abrasion, the number of small grains increases—partly because the larger grains are reduced in size and partly because small particles are broken off from the larger ones. And, inasmuch as abrasion of whatever type works more effectively upon the heavier and the softer minerals, it tends to increase the number of small magnetite grains much more than the number of small tourmaline grains.

This increased number of small mag-

[22] Barrell, *op. cit.*, pp. 330-331, 335-336, 338.
[23] Rubey, W. W., Geology of the Hardin and Brussels quadrangles, Illinois: *Illinois Geol. Survey Bull.* (Awaiting publication.)

netite grains, like the greater settling velocity of the magnetite grains, would clearly result in a greater concentration of magnetite in the finer grained portions of each separate deposit or sample of the sand. But, in one important respect, this increase of small magnetite grains would give a result quite different from that caused by settling velocities alone. Even though the number of magnetite and tourmaline grains of any given size may have been exactly equal at the source, continued abrasion might so alter the original ratio that, among the grains being swept along by the water and therefore available for deposition at favorable places, magnetite had become ten times as abundant as tourmaline in the small sizes and only one-tenth as abundant as tourmaline in the large sizes. That is to say, the small fragments resulting from abrasion would not necessarily or even probably be deposited along with the larger particles from which they were broken off; they would in large part be swept away by the currents at the first site of deposition and eventually dropped elsewhere. Thus the proportion of different heavy mineral grains would vary from one deposit to another even within the same stream. The heavier and softer minerals, having lost most by the abrasion, would be rare in the coarse deposits and abundant in the fine deposits.

This marked difference between the effects of settling and abrasion may be emphasized by stating the relationship in another way. Both processes tend to concentrate the heavy minerals in the finer grained portions of a given deposit. However, sorting, considered by itself, merely acts upon the mass of debris available to it in the load being transported. With a uniform distribution of sizes in the load, sorting causes the heavy minerals deposited in the finer fractions of a coarse sample to exceed the heavy minerals deposited in the coarser fractions of a fine sample; and, therefore, with standard methods of comparison, the coarsest grained samples appear to contain the most heavy minerals. The distance of transportation and the hardness of the different minerals play no part in their size-distribution as effected by sorting alone. The effects of abrasion, on the other hand, depend largely upon the distance of transportation and the hardness of the different minerals, and they tend to alter the proportion of different minerals in the various grain sizes in such a way as to oppose and eventually to overweigh the effect of sorting. Thus, as the result of continued abrasion, the heavy minerals deposited in the predominantly finer grained samples come to exceed the heavy minerals deposited in the predominantly coarser grained samples; and, whatever the basis of comparison of heavily abraded sandstones, the finer grained samples contain more of the heavier and the softer minerals.

THE EFFECT OF THE SIZE-DISTRIBUTION OF DIFFERENT MINERALS IN THE SOURCE ROCK

The question now very properly arises of how essential to our conclusions is the premise of a source rock of homogeneous composition, that is, one in which the relative abundance of quartz, magnetite, and tourmaline is

approximately the same in each grain size. This assumption is obviously an artificial one chosen merely for its convenience in computation. If large magnetite grains were rare, that is, if the $\frac{\text{quartz}}{\text{magnetite}}$ ratio, instead of remaining 100 to 1 throughout the range of sizes, became much greater among the larger particles, the distribution of the two minerals would be very different among these coarser fractions of all samples. Still, if this upper limit of homogeneous size-distribution were 0.354 mm. or larger, the relative abundance of different minerals among the grains less than 0.354 mm. in diameter shown in Tables 2, 3, 4, 5, and 6 would remain unchanged. If, however, these departures from homogeneity had also affected the smaller grains, the proportions of the different minerals in various size fractions would have been quite different. The full effects of any departures from homogeneity can be calculated only if the complete size-distribution of each mineral in the source rocks is known.

The writer is aware of no common, or at any rate no generally recognized, relationships of crystal sizes that result in marked differences in the grain size of the various mineral species present in igneous and metamorphic rocks. Perhaps such relationships actually exist, for the normal order of crystallization in magmas and the selective recrystallization of minerals during metamorphism record differences of chemical composition, solubility, and specific volume which are, in turn, undoubtedly related to differences of specific gravity and hardness. But the net effect of these differences appears to be too complex to serve as a basis for predicting the dominant sizes of the crystals of different minerals. Consequently, among at least the smaller mineral grains that make up igneous and metamorphic rocks, the assumption of a homogeneous size-distribution now appears justifiable, because any irregularities seem about equally probable in either direction and hence quite as likely to increase as to decrease the variations of heavy mineral proportions here discussed.

However, in source rocks made up of glacial deposits and of other sedimentary rocks, the size-distribution is clearly subject to influences that make this assumption err systematically in certain directions. During prolonged glacial motion, particles of the softer minerals probably suffer most from abrasion, so that in glacial tills the softer minerals may tend to be most abundant among the fine grains and the harder minerals most abundant among the coarse grains. Likewise, if the source were a sedimentary rock such as a water-laid sandstone, its constituent particles would have been subjected previously to sorting and to more or less abrasion. As we have seen, both sorting and abrasion tend to concentrate the heavier minerals in the finer grained portions of the deposits, and the latter tends also to concentrate the softer minerals in these finer grained portions. Consequently, the initial effect of a sedimentary source rock is likely to be very similar to that of long continued transportation before deposition—the proportion of different minerals being carried by the stream and

thus available for deposition would vary with the grain size. Any additional sorting or abrasion that precedes the second deposition only intensifies these initial variations in the size-distribution of the different minerals. It is perhaps of some interest to note in passing that this interpretation of the effect of a sedimentary source rock or of long continued abrasion upon the size-distribution of heavy minerals in a deposit offers a possible explanation of the occurrence of "flour" gold in very fine-grained deposits as contrasted to the more normal types of placers in coarse-grained deposits.

The precise effect of irregularities of the size-distribution of different minerals in the source rock, like that of abrasion during transportation, obviously depends upon different circumstances. Yet a rough approximation to the net effect of these two factors in ordinary deposits can perhaps be made by comparing the distribution of magnetite and quartz grains in some natural water-laid sands. Data for such a comparison are available in seven samples of magnetite-bearing quartz sand mechanically analyzed by Udden.[24] This comparison can be made most conveniently if Udden's data are replotted as cumulative[25] curves. Of the seven samples, two from the beach of Matagorda Bay, Olivia, Texas, in which all grains are less than ¼ mm. in diameter, follow closely the size-distribution of the two minerals expected from a homogeneous source rock and from Stokes' law of settling velocities. The distribution curves of the quartz and magnetite grains in these two samples have very similar shapes and are displaced so that the lower and upper size limits and the average diameter of the magnetite grains are approximately 63/100 as large as the equivalent sizes of the associated quartz grains. However, in the other five samples (one beach sand and four stream sands, in which essentially all grains are between ⅛ and 8 mm. in diameter) the distribution curves of the quartz and the magnetite grains are very different. In all five, the magnetite grains are much more perfectly sorted than the quartz grains and the curves are so displaced that the diameter ratios between approximately equivalent sizes of the magnetite and quartz grains decrease from about 0.85 in the finest sizes to about 0.15 in the largest sizes. This decrease of diameter ratios with increase of grain size is approximately what would be expected if Stokes' law gradually gives way to the square-root law between the silt and gravel sizes (pp. 17-19). But it is also precisely what would be expected as the result of derivation from a previously sorted sedimentary source rock or of considerable abrasion during transportation. Without much more information about each sample, it is impossible to say which of these possible causes has been most influential. For the present purpose, it is sufficient to note that the factors we have been discussing actually cause large variations in the size-distribution

[24] *Op. cit.*, pp. 727, 734-735.

[25] Wentworth, C. K., Methods of mechanical analysis of sediments: *Univ. Iowa Studies*, vol. 11, pp. 46-51, 1926; or, Rubey, W. W., Lithologic studies of fine-grained Upper Cretaceous sedimentary rocks of the Black Hills region: *U. S. Geol. Survey Prof. Paper* 165, p. 22, 1930.

of different minerals and that these variations are commonly such that they increase the contrast of heavy mineral proportions in coarse and fine samples.

THE EFFECT OF OTHER FACTORS

Certain other assumptions involved in the discussions of our theoretical sandstones need to be re-examined before any final conclusions can be drawn.

For one thing, the analysis has been restricted to water-laid sandstone. Other agents of deposition and transportation, notably the wind, would give quite different distributions of the heavy minerals. In fact, the very low density of air would lead us to expect that sorting by the wind would not cause nearly so pronounced a concentration of heavy minerals in the finer grain sizes as does sorting by water. Also, no effort has been made in this paper, beyond that involved indirectly in the choice of certain types of sorting for comparison, to contrast the effects of fluvial transportation and deposition with those of littoral transportation and deposition. Nevertheless, this neglect of the distinctly littoral processes, such as the zone of confused wave motion along beaches, appears to call for no significant qualifications of the foregoing results, because the laws of sorting and abrasion under these conditions are, after all, probably very similar to those under stream conditions.

However, the neglect of any consideration of weathering at the source and during transportation may be an important source of error. Decomposition would decrease the effective hardness and effective density of mineral grains; and, consequently, minerals like magnetite, which are relatively susceptible to weathering, would be more quickly ground down to finer sizes and eventually eliminated.

Then again, differences in the shape of different mineral grains have been ignored. It is true that, because of differences in the readiness of cleavage and the resistance to abrasion, the detrital grains of different minerals tend to have characteristic shapes. Nevertheless, so long as the comparisons do not include such micaceous minerals as biotite and muscovite, the neglect of shape differences is believed to introduce no very serious errors into the results.

One other assumption scarcely needs any special discussion. Had there been thirty different mineral species in the source rock instead of only three, the principles of sorting that govern their distribution in the deposits of sandstone would have been altered in no way. However, the rate of abrasion of each different mineral might have been affected somewhat, for this depends in part upon the dominant hardness of the other mineral grains being transported at the same time.[26]

Finally, the samples chosen for comparison range from fine-grained to coarse-grained sandstones. Other things being equal, the variation of the $\frac{\text{magnetite}}{\text{tourmaline}}$ ratio among grains of a certain size fraction in different samples would increase with the contrast in average grain size of the samples. Had we compared only moderately

[26] Barrell, *op. cit.*, p. 336.

coarse and moderately fine sand, the variation of the heavy mineral ratios would have been less; but had our samples ranged from gravel to silt, as do the materials of the Wisconsin and Illinoian stream deposits, the study of which led to the preparation of this paper, the variation would have been much greater.

CONCLUSIONS AND RECOMMENDATIONS

Apparently the assumptions made in discussing these theoretical sand samples have, in the aggregate, tended to minimize rather than to exaggerate the effects of the various factors that influence the proportions of different heavy minerals in sandstones. Many of the assumptions seem to demand no important qualification of the results either one way or the other because probable departures appear about equally likely to increase or to decrease the contrasts that were found. On the other hand, several of the assumptions seem clearly to err on the side of distinctly minimizing the heavy mineral contrasts that might be expected. Hence, the conclusion appears justified that, even in sandstones derived from identical source rocks, the heavy mineral assemblages taken from certain size fractions of the different samples may—either apparently or actually—depend largely upon the grain size or degree of sorting of the different samples. Stated another way, the relative abundance of two minerals in any particular size fraction of different sand samples depends upon a great many factors, only one of which is an actual difference of source rock. In general, the contrast varies with the difference in the density and hardness of the two minerals, with the difference in degree of concentration of the minerals in certain sizes at the source, with the amount of abrasion during transportation, with the degree of sorting at the site of deposition, with differences in the average grain size of the samples compared, and (because of the different law of settling velocities of the larger grains) with the absolute grain size of the samples.

If this general conclusion is accepted, it follows that, in making comparisons of heavy mineral assemblages from different sandstones for purposes of correlation or of information about the character of source rocks, the probable dependence of the assemblages upon these various factors should be borne in mind and, if possible, allowed for.

Both theoretically and practically, the most satisfactory method of allowing for these various factors would be to restrict all comparisons to the heavy minerals taken from comparable portions of sandstones that have essentially the same grain size and the same degree of sorting. This precaution would eliminate all the variations discussed in this paper, except those due to differences in the amount of abrasion. This single exception might, of course, be an important one—two sandstones might be derived from the same source rock and be exactly alike in grain size and degree of sorting yet, if one had been transported far from its source and the other only a short distance, the two could have very different proportions of heavy minerals. However, the effects of transportation

and abrasion cannot at present be estimated quantitatively; and any allowances made for these effects must rest upon regional paleogeographic considerations rather than upon the textural features of the samples. For many types of studies, perhaps this comparison of samples of the same grain size and same degree of sorting will be a sufficient precaution; but, with samples in which the grain size or the degree of sorting differs perceptibly, some other method of comparison must be sought.

If sorting were the only factor that affected the size-distribution of different minerals, it would clearly be advantageous to make the comparisons of the entire heavy mineral content of each sample. This separation of the entire heavy mineral content might be made from every one of the several size fractions into which each sample can be divided or, more directly, from each original unseparated sample itself. The first of these two methods would undoubtedly give the most complete information about the size-distribution of the heavy minerals in the samples, and for that reason it is to be preferred wherever conditions permit; but this method is subject to two practical disadvantages which decidedly limit its field of applicability. First, it is time-consuming, because it involves a great multiplication of laboratory work. Second, the use of the petrographic microscope for mineral identification sets a very effectual upper limit to the size of grains that can conveniently be studied after separation. Grains more than about ½ mm. in diameter call for a materially different technique of examination. Consequently, for all but the very finest grained sandstones, it is impracticable to make routine determinations of the heavy minerals in the coarsest grained size fractions of all samples. Separate determination[27] of the heavy minerals in each of the grain sizes less than some particular diameter still remains quite useful for certain purposes but, because of the practical difficulties involved, the determination of all the heavy minerals in each size fraction cannot readily be made in the study of a large number of samples.

The other possible method of comparing the entire heavy mineral content of each sample by making one heavy mineral separation from the entire sample encounters one of these same practical difficulties. With all but the very finest grained sandstones, this method yields grains too large to be examined conveniently under the microscope. It is also open to another and perhaps more fundamental objection in that it gives no data by which corrections can be applied for the possible effects of sorting, abrasion, or irregularities in the size-distribution of different minerals at the source.

The impracticability of comparing the entire heavy mineral content of each sample has naturally led sedimentary petrologists to the next step of comparing the heavy mineral grains from that portion of each sample which passes some particular sieve

[27] Trowbridge, A. C., and Mortimer, M. E., Correlation of oil sands by sedimentary analysis: *Econ. Geol.*, vol. 20, pp. 414-415, 419, 1925.

Graham, W. A. P., A textural and petrographic study of the Cambrian sandstones of Minnesota: *Jour. Geol.*, vol. 38, pp. 710-711, 1930.

mesh, so that, let us say, all heavy mineral grains with diameters less than 1/3 mm. in each sample are examined. This method has the great advantage of mechanical simplicity and speed, but it is open to serious objection if the samples to be compared vary appreciably in their grain size or their degree of sorting. As may be seen in Figure 3 and in Tables 3 and 5, the portions of different samples that will pass some arbitrary sieve mesh, such as 0.354 mm., may not be at all comparable in their heavy mineral content. The fraction so separated from a coarse-grained sandstone is only a very small and unrepresentative portion of the total sample. Figure 3 illustrates the disadvantages of this method where sorting is the only factor and where the proportions of the different heavy minerals depend solely upon the relative position of a size fraction within the general size-distribution curve of the sample. But it may also be clear from previous discussions in this paper that the heavy mineral separates obtained by this method are equally unsatisfactory for purposes of detailed comparison where abrasion and irregularities of size-distribution at the source are the controlling factors. Under these conditions, the relative abundance of the different heavy minerals vary not with the relative size but with the actual size of the grains. Hence, the separation of *all* heavy mineral grains less than some particular diameter tends to emphasize the variations due to abrasion and irregularities of size-distribution at the source, for the reason that the heavy minerals thus separated from the finer grained samples may include minerals concentrated only in the very finest sizes and so absent from the medium and coarser grained samples.

The practical difficulties that stand in the way of making routine comparisons of all the heavy mineral grains in each sample and the fundamental objections to comparing all "heavies" less than some particular size in each sample suggest that the best basis for comparison may be the heavy mineral crops separated from some one size fraction of each sample. This general method commends itself to many sedimentary petrologists, because it gives a maximum amount of information with a minimum expenditure of time.

Yet, even granting the convenience of comparing the heavy minerals of only one size fraction from each sample, there still remains the question of deciding what particular size fraction from each sample affords the best basis for comparison. Common practice apparently is to compare fractions of the same *actual* grain size from each sample, regardless of the average coarseness of the different samples. In two respects, this method of comparison is excellent: first, because it tends to eliminate the variations caused by abrasion and by irregular size-distribution in the source rock, and, second, because the color, pleochroism, and birefringence of the different grains are more nearly comparable when all grains under the microscope are of approximately the same size. However, this method, taken alone, is poorly adapted to discriminative comparisons of water-laid sandstones because, as we have seen (Tables 2, 4, and 6), it

tends to emphasize those very differences in heavy mineral proportions that are caused by sorting in water.

An alternative method would be to compare the heavy minerals from fractions that represent the same *relative* position within the size-distribution curve of each sample. That is, the comparisons may be made of fractions with a size, say, midway between the minimum and average diameters of each sample (for example, the fractions marked X in each of the three samples illustrated in Fig. 3). Among samples that have approximately the same degree of sorting, such comparisons would eliminate essentially all the variations of heavy mineral proportions that are caused by different settling velocities.

Still, even this method of comparing fractions with the same *relative* grain size is no cure-all. Its merits are least precisely where comparisons of fractions of the same *actual* grain size are greatest, because it tends to emphasize those variations that are caused by abrasion and by irregularities in the size-distribution of the different minerals at the source. Thus, neither of these two methods, used alone, gives all the information needed for careful comparisons. Fortunately, however, the two methods supplement one another very well and, used together, they indicate closely and with a minimum expenditure of time the actual size-distribution of the various heavy minerals in a group of samples.

Summarizing then, it appears that no one particular size fraction from a series of sand samples with different degrees of coarseness and sorting is best suited for detailed comparisons of the heavy mineral content. In order to make allowances for the variations in heavy mineral proportions due to sorting, abrasion, and irregularities at the source, the heavy minerals from at least two size fractions of each sample should be examined. These two fractions should be so chosen that one of them has the same *actual* size limits in all of the samples compared and the other represents the same *relative* size within the distribution curves of the different samples.

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COMPARATIVE TESTS OF SEVERAL METHODS OF SAMPLING HEAVY MINERAL CONCENTRATES

GEORGE H. OTTO
California Institute of Technology, Pasadena, California

ABSTRACT

When the total heavy mineral concentrate is larger than can be examined conveniently on a microscope slide, large sampling errors may be introduced during the selection of a portion for examination. Results are given of a series of tests, designed to ascertain both the most practical method of sampling very small amounts and the relative importance of various causes of sampling difficulties. New techniques for obtaining minute samples are described. The methods and conclusions may be applied to any mixtures of sand grade-sizes such as concentrates of microfossils.

STATEMENT OF THE PROBLEM

Heavy mineral concentrates, obtained by treating small portions of sand with heavy liquids such as bromoform, are often too large for mounting on a single microscope slide; in such cases some fraction of the total amount must be selected, unless one chooses to begin anew with a smaller amount of material. Even in the latter case, if the heavy minerals comprise a considerable fraction of the sand, the sample treated will be so small that the same kind of errors will be introduced which it is sought to avoid. In either case, sampling problems arise which differ mainly in the quantity of material to be handled.

The errors involved in sampling operations are of two kinds: simple errors of random sampling, which can be treated mathematically; and errors arising from conditions which shift the observed modal frequency[1] of a particular component from its true value.

If heavy mineral grains were alike in all properties except color a small sample could be selected at random from the well mixed whole and counted. The probability that the results obtained are not in error more than any specified amount could be computed without difficulty. A sample of sufficient size could then be selected to insure the degree of accuracy required. Dryden[2] has prepared a chart showing the probable error involved for different frequencies in samples of 25 to 750 grains. He concludes that for quantitative heavy mineral work, a count of 300 grains is an optimum number, and shows that the accuracy

[1] The observed modal frequency is that value of the percentage composition which tends to occur most often when a large number of slides are counted. For a more complete definition of this term and other statistical terms used in this paper, see: Secrist, An Introduction to Statistical Methods, revised edition (1925).

[2] Dryden, A. L., Jr., Accuracy in percentage representation of heavy mineral frequencies: *Nat. Acad. Sci. Proc.*, vol. 17, no. 5, pp. 233-238, 1931.

of the count increases as the square root of the number of grains counted. Dryden also shows that not more than two significant figures are justified when even as many as four thousand grains are counted.

The theory on which these calculations are based assumes that the condition of random sampling exists: i.e., the probability of drawing a particular kind of mineral grain is $n_1/n_1+n_2+n_3 + \ldots +n_n$ where $n_1, n_2, n_3, \ldots n_n$ are the respective numbers of grains present. If this condition is not completely fulfilled, the results obtained will be less accurate than the calculations predict.

It is very unlikely that the conditions of random sampling are even roughly approximated when samples are selected by means of a spatula, or poured from a vial, no matter how carefully the contents have been mixed, for the grains differ in size, shape, density, magnetic properties, coefficient of friction, and elastic properties. Thus magnetite grains tend to adhere to each other, increasing the apparent percentages; heavy grains sink rapidly through the mixture under even the slight shock of a thin spatula. Grains with low coefficients of friction slip away from the spatula more readily than grains with high coefficients of friction.

METHODS OF SAMPLING

Many mechanical methods have been developed for sampling relatively large masses of material. In all cases, the intention is to approximate the conditions of true random sampling in mixtures so heterogeneous that selection of a representative unit from one place is impossible. The method of coning and quartering is one such. Usually, considerable experimental difficulties are encountered when an attempt is made to apply these techniques to samples of five grams or less, and particularly when it becomes necessary to select a sample as small as a centigram from a gram or more of heavy mineral grains of diverse sizes and shapes.

Pettijohn[3] has suggested a simple method of quartering which gives good results if some precautions are taken which are not enumerated in the footnote. The method is very time-consuming, however; about fifteen minutes are required to reduce three grams of sand to a sample of 300 grains.

W. C. Krumbein of the University of Chicago has developed a mechanical method for quartering very small samples by which the grains are poured into a conical hopper whose very small opening at the tip is centered over the intersection of two knife edges set at right angles to each other. The sample is thus split into four approximately equal quarters. Two alternate quarters are rejected, and the remainder again passed through the device. This process is repeated until a sample of the proper size has been obtained. The writer has added several improvements, the final form being shown in figure 1.

[3] Pettijohn, F. J., The petrography of the beach sands of Southern Lake Michigan: *Jour. Geol.*, vol. XXXIX, footnote, p. 436, 1931.

The Jones ore sample splitter[4] has long been in use for obtaining samples of twenty-five grams or more from relatively large amounts of material. In this device, the sand is emptied into a long narrow hopper and is divided equally, the material falling into two pans by a series of inclined chutes; adjacent chutes slope in opposite directions. The contents of one pan are emptied again into the hopper. This is repeated as many times as needed to reduce the sample to the desired size.

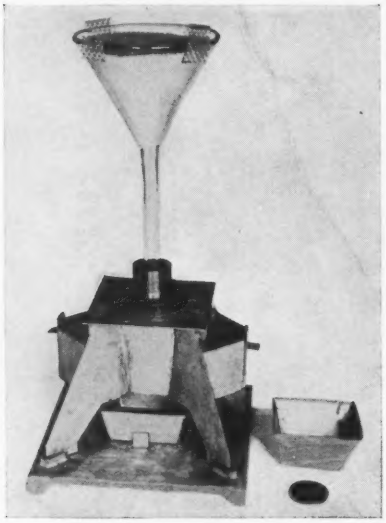

FIG. 1. Improved Krumbein method of sample splitting. The sample is emptied onto the screen in the glass funnel using one of the pans. Two opposite quarters collect in the pan beneath the device while the other quarters fall into little bins which need be emptied only when the device is cleaned. The empty pan is now interchanged with the one beneath, and the sample is again split in half. The process is repeated until a sample of the proper size has been obtained.

The chutes of the Jones sample splitter are constructed of folded sheet iron; such construction cannot be used in a device as small as required for the usual heavy mineral concentrates. For the inclined chutes, the writer used a series of sixteen brass plates each one-sixteenth inch thick with polished inclined edges; the plates were separated by very thin sheet bronze partitions. The parts were pressed together in a strong vise and screws inserted to hold the parts in place. The principle and mode of operation are the same as for the ore sample splitter, but the mode of construction has been completely changed. The Microsplit,[5] as the device is called, is shown in figure 2. In the tests which follow it will be shown that it is superior to the improved Krumbein method, the Pettijohn method, and far superior to using a spatula or pouring a few grains onto a slide from a vial. It takes only a minute to split a large sample to a few hundred grains, including fifteen seconds for cleaning.

METHODS OF TESTING

In order to test the relative values of the various methods of obtaining minute samples, a series of artificial mixtures of mineral fragments with definite size, shape, and density were prepared. Three minerals were chosen for each mixture to facilitate counting. The amount of each mixture prepared was sufficiently large that any errors introduced by withdrawing unrepre-

[4] Robert Peele, *Mining Engineers' Handbook*, Section 30, Article 1, p. 1751, 1918.

[5] The Microsplit and the Mineral Grain Mounting Cell, described later, may be obtained from Ferguson Engineers, 53 West Jackson Blvd., Chicago, Illinois.

sentative samples of a few hundred grains could be neglected. The well mixed grains were then passed through the Microsplit a sufficient number of times to obtain a sample of the desired size, usually 100-300 grains. The unused portion, which always amounted to 99% of the total, was again split to a sample of the same size. This was repeated four times. The remainder was then treated in the same way, using the improved Krumbein method. The Pettijohn method then was tried. Finally, since the spatula method is most apt to alter the composition of the mixture, samples were withdrawn with a spatula or were poured directly onto the slide from a tiny vial after first mixing thoroughly. When using this last method, special precautions were taken to select the sample from those portions which appeared most nearly to represent the composition of the whole.

FIG. 2. The Microsplit. The two receiving pans are shown in place. The third pan with which the material is emptied into the hopper, is shown setting near the device. The sample is emptied into the hopper and is divided into two equal portions. One of the receiving pans is now interchanged with the empty pan, and the sample again passed through the hopper. This process is repeated until the sample has been reduced to the proper size.

Eight different mixtures were studied by this procedure. The components of these mixtures were selected so that the influence of size, shape, and density differences, and the presence of magnetite could be studied nearly independently of each other. To what extent other properties such as differences in elastic properties and coefficient of friction are causes of sampling difficulties is not known, but the results of mixtures 1 and 2 indicate that though these factors do enter to some extent, they are of small importance compared with the other factors enumerated.

After the original mixture had been reduced to a few hundred grains, these were mounted on a microscope slide with the aid of a mounting cell devised by the writer to prevent the loss of any grains. It consists of a frame for holding the slide, and a rectangular cover plate one-half inch thick into

which a hole three quarters of an inch in diameter is drilled. This plate is allowed to rest directly on the glass slide, and the grains are emptied into the hole; four pins fastened in the frame and fitting into holes in the cover plate, serve to center the latter over the microscope slide. Unless the grains are very small, they will distribute themselves suprisingly evenly over the slide as a result of their collisions with the brass wall. Powdered piperine is added gently with a small spatula, and the cover plate is removed. The piperine is melted and a cover glass placed on the slide. The whole operation requires only two or three minutes.

Piperine was used because most common colorless minerals give distinctive dispersion borders which make instant identification possible. A binocular microscope employing slightly inclined illumination and fitted with a mechanical stage was used. Every grain on each slide was counted; most of the slides were recounted. If the counts differed by more than two grains in 300, recounting was continued until such a degree of concordance had been obtained.

The properties of the various mixtures studied and the purposes of using the mixture are set forth in Table I.

The column headed *computed frequency* represents an attempt to determine whether the various sampling methods give results which are close approximations to absolute values, or whether the results are useful for correlation purposes only. The method of computation and the assumptions are as follows:

Assume that three minerals are chosen which are essentially alike in cleavage and brittleness, and that the same method of crushing and screening has been employed in all three cases. Now consider those fragments which lie within a particular grade size. In each of the three cases the volumes will vary considerably from one grain to the next, but since the physical properties which tend to influence the relative amounts of fine material are essentially the same, the average volume of the particles within this grade size will be nearly the same for all three minerals. Let a mixture be formed of w_1 grams of a mineral of density d_1, and w_2 grams of a mineral with density d_2, and w_3 grams of a mineral with a density d_3. Let v be the average volume of the grains of the particular grade size employed; by hypothesis this is essentially a constant for the three minerals. Let p_1, p_2, p_3 represent the respective frequencies of the three minerals. These frequencies will be in the ratio,

$$p_1 : p_2 : p_3 = \frac{w_1}{vd_1} : \frac{w_2}{vd_2} : \frac{w_3}{vd_3}; \quad v(p_1 : p_2 : p_3) = \frac{w_1}{d_1} : \frac{w_2}{d_2} : \frac{w_3}{d_3}$$

From the ratios of the frequencies, the percentages can be calculated as follows: % of mineral 1 $= (p_1/p_1+p_2+p_3) \times 100$.

The excellent agreement in the cases of mixtures 1, 2 and 8 is evidence that at times the assumptions involved are fulfilled to a surprising degree. Also, there can be no doubt that when care-

TABLE I. PROPERTIES OF THE ARTIFICIAL MIXTURES STUDIED

Mixture Number	Components	Density[1]	Grade size	Weight taken	Computed frequency[2]	Mean observed frequency[3]	Other properties of components	Principal disturbing factor	Disturbing factors essentially absent
1	Grossularite Spinel Olivine	3.67 3.40 3.3	¼–⅛ mm. ¼–⅛ mm. ¼–⅛ mm.	0.54 g. 0.50 0.48	33.5% 33.4 33.1	33.4% 32.0 34.6	Synthetic $MgAl_2O_4$ fresh dunite used	None	Magnetic grains and large differences in size, shape, density
2	Olivine "dyed" violet[4] Olivine dyed red Olivine dyed blue	3.3 3.3 3.3	½–¼ mm. ½–¼ mm. ½–¼ mm.	2.00 1.00 0.50	57 29 14	58.1 27.9 14.0		None	Magnetic grains and large differences in size, shape, density
3	Olivine Spinel Grossularite	3.3 3.40 3.67	½–¼ mm. ¼–⅛ mm. ⅛–1/16 mm.	3.00 0.30 0.030		58.1 27.9 14.0		Size: large grains most abundant	Magnetic grains and large differences in shape and density
4	Olivine, dyed violet Olivine, natural Olivine, dyed pink	3.3 3.3 3.3	½–¼ mm. ¼–⅛ mm. ⅛–1/16 mm.	0.365 0.78 1.55		54.4 28.4 17.2		Size: small grains most abundant	Magnetic grains and large differences in shape and density
5	Cyanite Grossularite Epidote	3.64 3.67 3.47	⅛–1/16 mm. ⅛–1/16 mm. ⅛–1/16 mm.	3.00 1.00 0.31		69.4 22.8 7.8	Cyanite grains tend to be elongated and thus have larger aver. vol.	Shape: volumes of grains also vary	Magnetic grains and large differences in density and grade size
6	Pyrite Grossularite Quartz	5.0 3.67 2.65	½–¼ mm. ½–¼ mm. ½–¼ mm.	0.57 1.25 2.70	8 23 69	8.0 15.6 76.4		Density: light grains most numerous	Magnetic grains and large differences in size and shape
7	Pyrite Grossularite Quartz	5.0 3.67 2.65	½–¼ mm. ½–¼ mm. ½–¼ mm.	5.40 1.32 0.32	69 23 8	77.4 15.9 6.7		Density: heavy grains most numerous	Magnetic grains and large differences in size and shape
8	Almandite Pyrite Magnetite	4.04 5.0 5.2	¼–⅛ mm. ¼–⅛ mm. ¼–⅛ mm.	4.0 2.5 1.0	59 30 11	58.8 30.2 11.0	Magnetite grains were strongly magnetized	Magnetic grains present. Density not constant	Large differences in size and shape

[1] The density was determined on the ½–¼ mm. grade size.
[2] See text for method of computation.
[3] Based on slides sampled with the "Microsplit," the improved Krumbein method, and the Pettijohn method.
[4] Attempts to fix the dye by absorption on a silica gel were unsuccessful; the grains were merely coated with the dye.

All minerals used were crushed grains. The crushed material was washed and purified, then screened twelve minutes in a Ro-Tap Shaking Machine.

ful sampling methods are employed, the percentage frequencies differ little from the absolute values.

The column headed *mean observed frequency* gives the arithmetic mean of the values found in Table II in the columns headed *average per cent frequency*. The results obtained by sampling with a spatula or pouring the grains directly onto the slide are not included because the values diverge too widely from the other rather concordant values.

DISCUSSION OF THE RESULTS

Table II gives the results obtained when different methods of sampling are used. The values given under *average number of grains* per slide are arithmetic means of the actual counts of each component. These data are included to enable one to judge whether a particularly large deviation is the fault of the method used, or caused by counting a relatively small number of grains. The *average per cent frequency* is also an arithmetic mean. The *maximum deviation from the mean* is the greatest observed deviation. Very likely, if a much larger number of slides had been counted, some would show greater deviations. The values are for comparison purposes and serve to indicate the order of agreement which one may expect in actual heavy mineral work.

Mixtures 1 and 2 were designed to ascertain whether sources of sampling errors existed other than differences in size, shape, density, and the presence of magnetic grains. Mixture 2 was also intended to show how small a sample one might safely count without endangering the usefulness of the results. The deviations are somewhat greater than those anticipated from Dryden's theory. In mixture 2, the only variable factors tending to disturb random sampling must be the surface properties of the grains, which were changed by the introduction of coatings of different dyes; special precautions were taken to prevent any segregation according to size within the grade-size range which was colored. That disturbing factors are present to some extent, is indicated by the greater deviations appearing when mechanical methods are not used.

Mixtures 3 and 4 were designed to show to what extent large differences of grade size were a source of sampling difficulty. Whether large or small grains predominate seems to make little difference. If special care had not been taken in mixture 4, the samples taken with a spatula would have shown very large divergence.

Mixture 5 was intended to show the influence of shape on sampling errors; *no general conclusions can be drawn* from the one sample studied. Mixture 5 suggests that the presence of long stringy fragments (cyanite slivers) is not a disturbing factor as had been supposed. *This unexpected result may* originate in large part from the small *size of the grains used. Since the ratio* of surface area to other measurable physical properties rises so rapidly as the grade size is reduced, it is probable that large differences of size, shape, density, and magnetic properties have little influence on sampling operations *in the very fine grade sizes. Also, the* cyanite slivers seem to form a network

TABLE II. RESULTS OBTAINED BY DIFFERENT METHODS OF SAMPLING

Mixture No. and Disturbing Factor	Components	Sampled with the Microsplit				Sampled by Improved Krumbein Method				Sampled by Pettijohn Method				Sampled with Spatula			
		No. of slides Counted	Aver. No. of Grains per Slide	Average Per cent Frequency	Maximum Deviation from Mean	No. of slides Counted	Aver. No. of Grains per Slide	Average Per cent Frequency	Maximum Deviation from Mean	No. of Slides Counted	Aver. No. of Grains per Slide	Average Per cent Frequency	Maximum Deviation from Mean	No. of Slides Counted	Aver. No. of Grains per Slide	Average Per cent Frequency	Maximum Deviation from Mean
1 Control	Grossularite	4	189	34.2[1]	1.2	4	172	32.6[1]	2.8	3	232	33.5[1]	0.4	3	144	36.0[1]	2.0
	Spinel		174	31.3	2.7		167	31.2	1.8		229	33.5	2.6		140	35.1	1.4
	Olivine		187	34.5	2.8		194	36.2	2.4		231	33.0	2.2		114	28.9	2.4
			550				533				692				398		
2 Control	Olivine, dyed violet	5	97	57.4	3.6	4	59	59.0	7.4					4	99	58.2	5.6
	Olivine, dyed red		49	28.5	2.9		27	27.0	8.5						42	24.8	7.0
	Olivine, dyed blue		24	14.1	2.4		14	14.0	3.5						28	17.0	3.1
			170				100								169		
3 Size varied	Olivine	4	320	55.4	2.2	4	390	53.5	4.5	See footnote [2]				0			
	Spinel		163	28.3	2.8		208	28.4	2.4								
	Grossularite		94	16.3	1.4		130	18.1	2.7								
			577				728										
4 Size varied	Olivine, dyed violet	4	319	73.2	3.0	4	255	65.7	3.5					3	332	69.7	7.8
	Olivine, natural		84	19.2	0.7		102	26.4	1.5						101	22.0	8.6
	Olivine, dyed pink		33	7.6	2.5		31	7.9	2.0						41	8.3	1.7
			436				388								474		
5 Shape varied	Cyanite	4	182	61.9	2.5	4	351	60.4	2.5					3	256	67.3	5.5
	Grossularite		94	32.1	2.2		194	33.4	2.5						104	27.0	4.2
	Epidote		18	6.0	0.7		36	6.2	0.6						22	5.7	1.3
			294				581								382		
6 Density varied	Pyrite	4	34	8.0	1.2	4	34	8.0	2.4					3	12	3.9	4.0
	Grossularite		63	15.1	1.9		66	16.1	2.3						47	15.8	6.1
	Quartz		324	76.9	2.4		303	75.9	4.1						242	80.3	5.8
			421				403								301		
7 Density varied	Pyrite	4	394	78.0	3.1	4	499	76.8	1.0					3	382	57.0	23.2
	Grossularite		77	15.3	2.8		110	16.6	1.6						171	30.6	16.4
	Quartz		34	6.7	1.0		42	6.6	0.9						71	12.4	6.8
			505				651								624		
8 Magnetite present	Almandite	4	271	59.7	5.4	4	179	57.9	2.3					4	400	60.3	1.9
	Pyrite		137	30.2	3.7		93	30.2	2.9						193	28.9	3.9
	Magnetite		46	10.1	1.7		37	11.9	1.1						71	10.8	2.8
			454				309								664		

[1] The use of three significant figures has been a custom in heavy mineral studies. These data clearly show the uselessness of the third significant figure.
[2] The Pettijohn method gave excellent results in some earlier tests in which size and density were varied.

which serves to enmesh the more equidimensional grains.

No experiments were made to determine the influence of rounded grains associated with euhedral grains. Observations on heavy mineral concentrates studied in the University of Chicago laboratory suggest that well rounded grains are a serious source of sampling error when combined with differences of size.

Micaceous heavy mineral concentrates from the West Coast Miocene beds offer the greatest sampling difficulties yet encountered. Only by sharply jarring the Microsplit after each passage of the sample through the device, can an excessive accumulation of mica in the final sample be prevented.

Mixtures 6 and 7 were designed to find out whether predominating heavy or light minerals offered the greater sampling difficulties. Mixture 6, in which quartz predominates, corresponds to a sediment before the heavy minerals are separated. Mixture 7, in which the high density mineral predominates, resembles the beach placer type. In mixture 7, the samples taken with a spatula gave unusually divergent mean values compared with the other two closely agreeing mean values. These results indicate that less error is likely to be introduced if the sample is reduced as much as possible before the heavy mineral separation.

TABLE III. PERCENTAGE COMPOSITION OF SUCCESSIVE SAMPLES TAKEN FROM AN ARTIFICIAL MIXTURE HIGH IN MAGNETITE

Sampling Method	Early Form of Microsplit			Thin Zinc Spatula		Knife Blade
Components	Slide 1	Slide 2	Slide 3	Slide 4	Slide 5	Slide 6
Magnetite	37%	38%	33%	41%	29%	91%
Hornblende	22	27	26	22	30	3
Augite	11	11	13	12	14	1
Epidote	6½	4	6	6	5½	1
Staurolite	7	7	6	6	7	2
Almandite	5	3½	3	4	4	1
Grossularite	2	4	4	2	2	½
Dark Tourmaline	5	3	6	4	5	TR.
Pink Tourmaline	1½	1	2	1	3	TR.
Hypersthene	2	1	1	2	2	TR.
Grains Counted	459	571	409	518	455	497

Crushed fragments were used. Grade size is essentially constant. (50–60 mesh.)

Mixture 8 shows the influence of a small amount of magnetite. The relatively large deviations from the mean when the Microsplit was used are left unexplained. Since the absolute magnitude of the deviations is never large, it appears that small amounts of magnetite are a minor cause of sampling difficulties.

The influence of large amounts of magnetite was studied before the Microsplit was fully developed. The results using this preliminary model of the device are shown in Table III.[6] Magnetite is here a large source of error except when this early form of the Microsplit was used.

[6] This table was presented orally at the Cordilleran Section of the Geological Society of America meeting, April 1932.

Mixtures 1, 2, 5, and 8 represent conditions more extreme than encountered in nature. The use of such mixtures is justifiable in order to show clearly what factors are causes of sampling difficulties. In actual work, it may be that some sources of errors tend to cancel each other; most are probably additive; some may multiply errors.

This investigation was undertaken to find a rapid means for obtaining concordant results in heavy mineral work on beach and dune sands and tills; it was the glaringly discordant results usually obtained in this work which forced the problem to the attention of F. J. Pettijohn and W. C. Krumbein who in turn interested the writer.

CONCLUSIONS

In those heavy mineral studies in which it is necessary to select a sample of grains from a relatively large amount, serious sampling errors are likely to arise unless some mechanical method is employed. These errors are caused by large differences in size, shape, and density, and the presence of magnetite. To a lesser extent the coefficients of friction of the grains on each other and possibly other elastic properties are sources of error.

It has been shown that large errors are likely to arise when the sample is selected from the well mixed mass of grains by the usual procedure of pouring a few grains from a small vial or selecting a portion with a spatula. Three mechanical methods were tested: the Microsplit ranked first in giving concordant results and requires the least time for operation, about one minute. The Pettijohn method gives quite satisfactory results as far as the limited tests show, but the time involved is so great, being ten to twenty minutes for a large concentrate, that its use seems to be limited to research work. The improved Krumbein method requires just twice as long to operate and clean as the Microsplit, and yields decidedly inferior results.

A method for computing the numerical frequencies of mineral fragments in certain artificial mixtures was developed, and found to give results good to one part in fifty when the assumptions on which it is based are complied with.

ACKNOWLEDGMENTS

The writer wishes to acknowledge the helpful advice of I. Campbell and R. Engel of the faculty of California Institute of Technology, and F. J. Pettijohn and W. C. Krumbein of the University of Chicago. The physics departments of both schools cooperated in permitting access to the facilities of the student shops.

JOURNAL OF SEDIMENTARY PETROLOGY, VOL. 3, NO. 1, PP. 40-43, FIG. 1,
APRIL, 1933

DISAGGREGATION OF CLASTIC ROCKS BY USE OF A PRESSURE CHAMBER

G. L. TAYLOR AND N. C. GEORGESEN
State University of Iowa, Iowa City

ABSTRACT

A pressure chamber of steel casing was used to disaggregate rocks in preparation for mechanical analysis. The apparatus is efficient for specimens not readily broken down by ordinary methods. Numerous solvents were forced into the pores of the rocks and allowed to dissolve the cement. The force of crystallization of sodium sulphate was utilized to disaggregate some rocks.

A difficult part of the mechanical analysis of many clastic rocks is the disaggregation of the rock without breaking or crushing the constituent grains. Disaggregation without breakage is necessary if accurate size and shape analyses are to be made. The method described in this paper was first used by the authors in 1930 at the University of Iowa, and since that time has been useful to other students working in the same laboratories. The writers are grateful to Prof. A. C. Tester for his helpful suggestions during the construction and trials of the apparatus.

Clastic rocks were disaggregated by placing them in a pressure chamber where they were subjected to pressures as high as 350 pounds per square inch and to accompanying high temperatures. A solution of sodium sulphate was used on some samples, and solutions to dissolve the rock cement were used on other samples which could not be disaggregated simply by the use of heat and pressure.

The disaggregation of the rocks into their components appears to have been due to one or sometimes a combination of several factors. According to the materials used the conditions of separation are given below:

1. High temperature alone will sometimes disrupt a rock of heterogeneous mineral content into its constituent grains since the different minerals have different coefficients of expansion.

2. Steam, other vapors, or solutions, forced into a rock under pressure, tend to enlarge the interstitial spaces and disaggregate the constituent grains.

3. Solvents, forced into a rock by steam under high pressure, will dissolve the cementing materials and free the grains.

4. If a supersaturated solution of sodium sulphate is forced into a rock at a high temperature and the rock is allowed to cool and dry, the sodium sulphate will crystallize with such force that the rock will be disaggregated.

Steam under pressure was used by

Driver[1] in recovering fossils from sedimentary rocks, but the maximum pressure of 22 pounds per square inch used by him was much lower than that used by the authors in their experiments with this method.

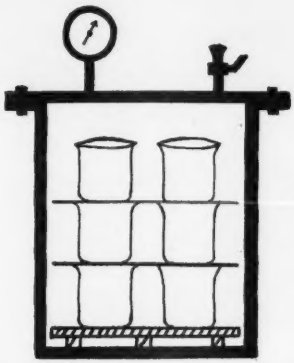

FIG. 1. Cross section of steel pressure chamber. Inside diameter 10 inches. Height 12 inches.

A variation of the fourth method listed above was used by Morris[2] in testing rocks to be used for road construction. His procedure was to soak a rock in a solution of sodium sulphate at atmospheric pressure, then dry the sample and allow the sodium sulphate to crystallize, utilizing the force of crystallization to break the rock.

The chamber (see figure 1) was constructed from an ordinary ten inch steel casing twelve inches long. A plate of one-half inch steel was welded to one end to form the bottom of the chamber. A flange one and one-half inches wide of the same material was welded to the outside of the other end of the casing. A cover of one-half inch steel, fourteen inches in diameter, was bolted to the flange with one-half inch bolts. A heavy composition boiler gasket was placed between the cover plate and the flange to prevent the escape of any vapor. Holes were provided in the cover to accommodate a one-fourth inch stopcock and a pressure gauge. Gas torches applied at the base of the chamber furnished the heat which produced pressures as high as 350 pounds. For higher pressures special heating and insulating equipment would be needed and a safety valve should be provided.

A rack made of strips of wood one-half inch in diameter placed one-half inch apart was placed inside the chamber to prevent the glass beakers containing the samples from sticking to the steel bottom of the chamber. By using temporary dividers a second and a third level of beakers was placed in the chamber. The dividers were made by cutting numerous one-half inch holes in heavy circular boiler gaskets ten inches in diameter.

In disaggregating specimens a separate beaker was used for each sample and enough water or solution added to completely cover the sample. The beakers were then stacked tier on tier in the chamber and enough water or solution was poured into the chamber to bring the level of the liquid about half way up on the sides of the bottom beakers. After the head of the chamber had been securely bolted on, heat was applied until the vapor formed from the solution in the bot-

[1] Driver, Herschel L., An aid in disintegrating samples for micro-organic study: *Jour. Paleontology*, vol. 1, p. 253, 1930.

[2] Morris, Mark, Unsoundness of certain types of rocks: *Iowa Acad. Sci. Proc.*, vol. 38, pp. 175-181, 1931.

tom of the chamber created a pressure sufficient to force the solution in the beakers into the samples as a liquid. At the completion of an experiment the samples were found covered with liquid, except when the vapor was permitted to escape so rapidly that the liquid was pulled out with it. When a sodium sulphate solution was used, the samples were allowed to cool and dry after they had been removed from the chamber so that the sodium sulphate in the rock would have time to crystallize completely before the samples were washed.

Solvents were used to free the constituent grains of clastic rocks in which the cementing material was a calcareous, a ferruginous, or a siliceous compound. At different times saturated solutions of hydrogen sulphide, stannous chloride, solutions of five to thirty-five per cent hydrochloric acid, and combinations of these solutions were tested for dissolving ferruginous cements. Tester[8] found that the stronger acid solutions containing stannous chloride gave the best results with rocks tightly cemented by ferruginous compounds; the same solutions were satisfactory in the authors' experiments. A two-tenths normal sodium hydroxide solution proved satisfactory for dissolving siliceous cements. Rocks held together by calcareous cements were readily disaggregated in weak acids. As far as could be determined the solutions dissolved the cementing materials without appreciably affecting the constituent grains of the rock. A weighed pebble of quartz was included in each sample to check the effect of the solutions on crystalline silica and the solvent action on the crystalline silica was found to be negligible.

Sodium sulphate was used to disaggregate rocks by the force of crystallization. As this solution is more soluble in hot water than in cold water, a large amount of the salt was necessary in each beaker so that even at high temperatures the solution would be supersaturated. By using such a supersaturated solution a large amount of sodium sulphate was driven into the rock. In the authors' experiments this method was more efficient than attempting to dissolve the cement of tightly cemented rocks. Because of the high temperature it is possible that some of the sodium sulphate reacts with the rock, but no evidence of this was observed.

After experimenting with conglomerates, gritstones, sandstones, siltstones, and shales, cemented with calcium carbonate, iron, silica, or mixtures of the three cements, it was concluded that steam or other vapors at 350 pounds pressure can be driven into nearly all the interstitial spaces of most sedimentary rocks. This was not true of a few highly compacted and tightly cemented rocks, nor of very large hand specimens. In such cases higher pressures probably would be more effective.

All the types of sedimentary rocks used were weakened by subjecting them to appropriate solutions under pressure. Many of the specimens were completely disaggregated. Most of those not completely disaggregated

[8] Tester, A. C., The Dakota Stage of the type locality, Appendix A, Laboratory Methods: *Iowa Geol. Survey*, vol. 35, p. 305, 1931.

were weakened sufficiently to make it possible to complete the process of disaggregation by tapping the sample with a rubber mallet. A specimen of very fine-grained, compact, siliceous cemented Chemung sandstone yielded very little to this treatment. This rock and siltstones of similar character were the only types encountered which were not successfully disaggregated.

The ease of disaggregation of clastic rocks varies with the compactness of the rock and the composition of the cementing material around the grains. In most cases the best solution to use for this work is a supersaturated solution of sodium sulphate. Covering each sample with a liquid, whether water or some solution, is very important, for in the authors' experiments specimens placed in dry beakers and subjected to the action of vapor only, showed very little disaggregation as compared to identical samples placed in beakers filled with liquid.

The efficiency of using a pressure chamber for the disaggregation of clastic rocks was demonstrated when the writers were able to disaggregate samples of certain siliceous conglomerates in three hours while other students had spent four months disaggregating the same conglomerates by the usual methods. Fortunately the apparatus required is neither unduly expensive nor difficult to use.

NOTES

A SUGGESTED MODIFICATION OF THE PIPETTE METHOD

In a recent number of this journal, W. C. Krumbein[1] describes in detail the technique and underlying principles of the pipette method for analyzing fine-grained sediments and recommends it for the use of sedimentary petrologists. As stated in Krumbein's paper, it has been the practice at the University of Chicago to mix the suspension by shaking after each sample is withdrawn. The time required to run one analysis to 1/1000 mm. diam. is approximately 26 hours. The writer in using this method in connection with the study of varved clays, wondered if it might be possible to reduce the time required for running each analysis.

Apparently all of the early workers, with the exception of Jennings, Thomas and Gardner,[2] assumed that the insertion of a pipette and the withdrawal of 20 cc. of suspension would set up convection currents and interfere with the settling of the remaining particles. The writer, without knowledge of the work of Jennings, Thomas and Gardner, challenged this assumption empirically, by running a number of analyses of the same material under the same conditions, allowing one set to settle continuously but shaking the other set after each sample was removed. This reduces the time required to 15½ hours, a saving of over 10 hours. Jennings, Thomas and Gardner used continuous settling for particles less than 1/200 mm. in diameter, but their apparatus and the time taken to withdraw a sample was quite different than that used by the writer.

PERCENTAGES IN INDIVIDUAL SIZE GRADES

Diam. in mm.	Field Sample No. 176S											
	Shaken						Not Shaken					
	2	4	6	8	Av.	Cum. Av.	1	3	5	7	Av.	Cum. Av.
>1/64	5.2	4.2	4.8	4.3	4.6	4.6	5.7	5.5	4.1	5.2	5.1	5.1
1/64–1/128	36.6	37.7	38.9	38.3	37.9	42.5	36.7	37.2	38.1	38.3	37.6	42.7
1/128–1/250	35.5	36.9	36.3	36.8	36.6	79.1	35.9	35.6	37.3	36.1	36.2	78.9
1/250–1/500	13.8	12.9	12.9	13.4	13.2	92.3	13.2	14.4	13.5	11.9	13.2	92.2
1/500–1/1000							4.2	4.4	4.2	4.9	4.4	96.6
<1/1000							4.2	2.8	2.7	3.4	3.3	99.9

The results of the writer's experiments are listed in the accompanying table. The rate of withdrawal of suspension averaged approximately 1 cc. per second. The only condition varied was the continuous or non-continuous settling. The experiments show very clearly that the amount of material both in the individual size grades and in the cumulative percentages are essentially the same for the two conditions of analysis. The largest variations are in the coarsest size where the methods used were identical. For the analysis of

[1] Krumbein, W. C., The mechanical analysis of fine-grained sediments: *Jour. Sed. Petrology*, vol. 2, pp. 140-149, 1932.

[2] Jennings, D. S., Thomas, M. D., and Gardner, W. A., A new method of mechanical analysis of soils: *Soil Science*, vol. 14, pp. 485-499, 1922.

sizes below 1/1000 mm. diameter the time saved is very much greater.

The idea of continuous settling for the pipette method is not original with the writer. The experimental material (summer fractions of varved clays) was essentially the same in all experiments. The writer believes that the saving of time, approximately 10 hours, as shown by this purely empirical test, justifies his recommendation of this modified technique to the consideration and certainly, to the further experimentation of workers in the finer sediments. These experiments also show the experimental error involved in analysis by the pipette method. In addition, this modified technique, by eliminating the necessity for a shaking or stirring device, will also greatly simplify any machine designed to mechanize the pipette method.

Diam. in mm.	Field Sample No. 181S										
	Not shaken						Shaken				
	1	3	5	7	Av.	Cum. Av.	2	4	6	Av.	Cum. Av.
>1/64	2.3	3.1	1.6	2.8	2.6	2.6	3.4	3.5	2.4	3.1	3.1
1/64–1/128	21.7	21.7	22.5	20.3	21.5	24.0	22.7	21.3	21.5	21.8	24.7
1/128–1/250	38.9	40.2	40.8	40.1	40.0	64.0	36.9	36.8	39.9	37.9	62.8
1/250–1/500	21.7	22.4	21.3	21.9	21.8	85.9	22.5	23.8	21.5	22.6	85.4
1/500–1/1000	9.1	5.8	8.1	8.0	7.7	93.6	8.2	7.3	8.3	7.9	93.3
<1/1000	6.1	6.7	5.6	6.7	6.3	99.8	6.1	7.1	6.2	6.5	99.8

GORDON RITTENHOUSE
University of Chicago

A CENTRIFUGE TUBE FOR HEAVY MINERAL SEPARATIONS

The use of an ordinary centrifuge tube for the separation of heavy minerals of a fine grained rock rarely leads to satisfactory quantitative data. The purpose of this note is to describe an inexpensive and permanent centrifuge tube which makes a rapid and efficient separation of grains smaller than one-half mm. Brown[1] described a tube which also works satisfactorily but is partially destroyed after each separation.

The design of the modified tube shown in figure 1 was suggested by Prof. A. C. Tester. This tube differs from the ordinary centrifuge tube in the shape of the lower part (D), and in the use of a movable cone-shaped stopper (A) and glass rod (B) inside the tube. The lower and smaller part of the tube joins the upper part at an angle of approximately thirty degrees. A cork-tipped plunger (A) fits on the shoulder (E). Into the glass cone at the lower end of the rod is fitted a cone-shaped cork (A) which is slightly larger than the constricted part of the tube so that it completely separates the two parts of the tube when the cork is in position. A cork (C) is provided for the opening of the centrifuge tube and fits tightly on the stem of the plunger so that the plunger will remain in any desired position; this makes it possible to close the heavy mineral chamber or to leave it open to provide for the passage of the minerals, whichever is desired.

For the best results the following procedure is suggested: (1) fill the tube to

[1] Brown, I. C., A method for the separation of heavy minerals of fine soil: *Jour. Paleontology*, vol. 3, no. 4, pp. 412-414, Dec., 1929.

the proper level with bromoform or other desired liquid of high specific gravity; (2) insert the plunger and press the cone-shaped stopper into position on the shoulder of the constricted part of the tube; (3) slowly pour into the tube a thoroughly dried portion of the sample; (4) place the cork at the mouth of the centrifuge tube to hold the plunger in central position; (5) shake the tube carefully to break any aggregates of grains in the liquid; (6) centrifuge for a few seconds to partially separate the minerals into heavy and light groups; (7) withdraw the cone-shaped stopper to a position about three-quarters of an inch above the constricted part of the tube; (8) place the tube in the centrifuge and whirl for a period of several minutes.

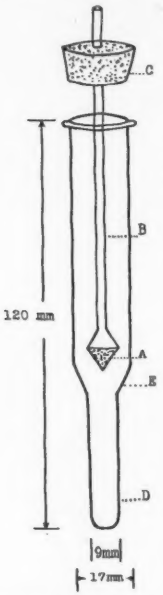

FIG. 1. Outline sketch of centrifuge tube used for heavy mineral separation.

When the centrifuging is complete, the light and heavy fractions may be removed easily by following these suggestions: (1) hold the plunger in position so as to act as a stopper for the lower part of the tube, and, at the same time, remove the cork at the mouth of the tube; (2) pour out the liquid in the upper part of the tube which will carry with it all the light minerals; (3) if the grains cling to the side of the tube or to the glass plunger, rinse them out with benzol or some other liquid; (4) remove the cone-shaped stopper and pour out the liquid and mineral grains from the lower part of the tube into a separate container; (5) if necessary wash this part of the tube also to remove any grains sticking to the glass.

Variations of this model of centrifuge tube have been constructed and tested. The type illustrated has been found most satisfactory and will make separations with a high degree of accuracy in about ten minutes. By running duplicate samples it has been determined that in quantitative analyses of light and heavy minerals made with this tube the per cent of error is negligible.

G. L. TAYLOR

University of Iowa
Iowa City, Iowa

A CLASSIC OF SEDIMENTARY PETROLOGY

I have found no reference in petrologic literature to the following work, though it is quoted by some hydraulic engineers:

Fugger, Eberhard, & Kastner, Karl: Die Geschiebe der Salzach (Geschiebe des Donaugebietes, 1., Donau-Studien nach dem Plane und den Instructionen von Dr. Jos. Ritter v. Lorenz-Liburnau, Dritte Abhandlung.) S. 146, Taf. 1. Beilage zu Band 38 der Mittheilungen der k. k. geographischen Gesellschaft in Wien, 1895.

Twenty-six thousand pebbles were collected by Fugger and Kastner from the bed of the Salzach at six well-chosen localities, and all were classified as to size and kind. Twenty thousand of these were also classified as to shape. The authors, because of their thorough knowledge of the areal geology of the whole drainage basin of the Salzach, were able to deter-

mine rather exactly the sources of the pebbles, and to calculate the durability of the various types of rocks.

The finer portions of the original samples were also given some study. Porosities were indirectly determined. Experiments on the solubility of the rocks were carried out.

The Salzach has alternating steep and less steep stretches. The authors conclude that the steeper the grade the larger the pebbles which the river is able to move, a conclusion as to cause and effect which is exactly reversed by some other writers. It is also concluded that the abundance of more or less angular blocks (nowhere less than 88% of the total), taken together with the decrease in average size downstream, indicates that the pebbles are reduced in size more by cracking up into smaller pieces than by rubbing down of surfaces.

I am acquainted with no other study of sediments which equals this one in respect to complete and exact determination of the sources of the materials.

A. O. WOODFORD

Pomona College
Claremont, California

REVIEWS

TWENHOFEL, WILLIAM H., and collaborators. *Treatise on Sedimentation,* Second Edition; The Williams & Wilkins Co., Baltimore, 1932; xxix + 926 pp., 121 figs., 91 tables. $8.00

The first edition of the *Treatise* was published early in 1926 with such success that the work of a complete revision was started almost immediately. With a few exceptions the collaborators are the same as for the first edition. There has been a marked increase in the knowledge relating to sediments since the material was gathered for the first edition and experience with the subject matter has aided in uncovering many references overlooked in the first writing. The literature pertaining to each subject discussed is reviewed more completely than in the first edition, and in most cases more interpretations and suggestions are offered by the authors.

The new edition shows an increase in the number of pages, illustrations, tables and references. The book is slightly thinner than the first edition although there has been an increase of almost forty per cent in the number of pages and the number of illustrations has been doubled. Each page carries three more lines of the same size type; this is equivalent to an increase of over sixty pages. The use of a thinner paper and the printing of many of the illustrations in the text has helped to reduce the thickness of the book.

The plan and organization is the same as used in the first book. In several cases where the subject matter was entirely rewritten the minor headings have been changed. The increase in amount of material is well distributed throughout the book. No increase is made in Chapter IV on Sediments and Organisms and there is a slight decrease in the number of pages devoted to Chapter VIII on Field and Laboratory Studies of Sediments. Chapter V on Products of Sedimentation has been increased almost fifty per cent from 280 to 416 pages and Chapter VI on Structures, Textures and Colors of Sediments shows an increase of exactly fifty per cent. The other four chapters have the normal increase of about 35 per cent. The number of bibliographical references (including repetitions and some footnotes) has been increased 58 per cent to a new total of 2252. This means a bibliography of over 1800 titles in many languages to the literature on sediments. The bulk of the references are from publications printed in English but the French and German literature has contributed a large number of articles. The practice in several countries of printing scientific reports in one of the above named languages helped materially in making the bibliography more complete.

Every chapter of the new edition can be commended as an improvement over the

first book. Space will not permit a detailed comparison of subjects but such an analysis shows that every part of the book has had careful revision and in many instances a complete rewriting. Wherever new material has been available it has been incorporated in the text; wherever the first writing did not make satisfactory statements of old material these parts have been revised. Some of the subjects which are more satisfactorily treated may be noted briefly: the origin of loess; the work of bacteria in muds during deposition, especially in lakes; the sediments derived from high regions of topographic youth and the explanation of flysch and molasse deposits; the effect of climate or change of climate on soils; the recognition of forest and prairie fire as a process affecting the amount and kind of sediments; the revision of the chapter on Sediments and Organisms with increased emphasis on the work of scavengers; the deposition of calcitic and dolomitic limestones; the entire discussion on "Red Beds"; the new grouping of coals in two types, (1) banded coals (2) massive coals, and the revision of the discussion of the various subtypes; the characteristics and origin of glauconite; the deposition of various salts; the complete revision of material relating to manganese in sediments; the discussions of cross lamination, unconformities, concretions, cone-in-cone and stylolites; the descriptions of sand holes, spring pits and sand domes; the discussion of colors of sediments; the discussion of realms of deposition, especially of lakes; and the note of caution on the interpretation of rhythms of sedimentation.

Of particular importance should be mentioned the increased attention given in several parts of the book to the minerals of sediments. Much new material is presented concerning sedimentary feldspars; the discussion of zeolites, meerschaum and other miscellaneous minerals is new. The use of detrital minerals in the determination of the character of the land surface and processes of erosion is emphasized. Much work has been done on this subject since the writing of the first edition and recognition has been given to the American as well as British workers.

The Chapter on field and laboratory studies has been rewritten but its brevity will be disappointing to many students.

The composition of the book is excellent. For a book of this magnitude the errors are remarkably rare. In a few places poor type or wrong font is seen. In the text reference to table 42 the analyses of four bentonites are mentioned but table 42 actually shows only three. In table 21 the temperature values have been omitted. In several cases new cuts have been made from the photographs used in the old edition but no correction has been made in the magnification mentioned in the text or explanation, as may be noted in figure 61.

Any student of sediments will find the new Treatise indispensable as a reference book, and as a source book for teaching purposes it is incomparable. The earnestness of Professor Twenhofel to correct the objections made to the first edition will be appreciated.

A. C. TESTER
Iowa City, Iowa
November 21, 1932